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Theoretical and Methodological Substantiation of Boundaries and Integrity in Landscape Cover and Its Components

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Abstract—Four main models of the appearance of boundaries (in a particular case, integrity), arising from the theory of nonlinear dynamic systems, are considered briefly. On the basis of Kotelnikov's fundamental sampling theorem and, accordingly, general information theory, the character of a distinguished boundary as a function of the sampling frequency in a spatial series with a regular step is investigated and the measurement unit "berg" (one full oscillation per one kilometer) is introduced, which is essentially identical to the unit "hertz" for a time series. The main provisions are illustrated using the analysis of the properties of real biogeocenoses and multispectral measurements of solar radiation reflection by the SPOT 6 satellite.

Keywords: topology, sampling theorem, scale, bifurcation, hysteresis, diffusion, feedback

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INTRODUCTION

The problem of the reality of boundaries has been the subject of discussion for two hundred years since the beginning of the formation of geography as a science. At the end of the 18th century, it was already generally accepted to consider all natural phenomena (inorganic, organic, social) as functional relations of parts of a single whole. The idea of integrity could also be expressed in the characteristics of each specific area. For example, Butte in 1811 stated: "no scientist doubts the existence of an earthly organism" (cited in Hartshorne, 1939). For Butte, individual countries and regions were "organisms," which, similarly to any organism, included physical and mental entities, with the main being the basis of the latter. However, as always in science, there was also a significantly opposing point of view on reality. Opponents of hyperintegrity drew attention to the fact that it is difficult to find regions that would be isolated by the boundaries simultaneously for all phenomena. The most complete criticism of this "holistic" concept was given by A.L. Bucher in 1827. Ultimately, he came to the conclusion that there is no need to study boundaries and that regions can be distinguished in any arbitrary way. He argued that geography should study the relationships of specific phenomena on any part of the Earth's surface (cited in Hartshorne, 1939).

The issue of integrity was most acute for the biotic component of the landscape, the vegetation cover. At the beginning of the 20th century, Morozov (1913, 1928) and Clements (1905, 1936) independently regarded plant communities as separate organisms. Gleason (1917, 1939) and Ramensky (1924) formulated the hypothesis of vegetation continuity. It was especially fully proved in the works by Ramensky (1910, 1924) with extensive statistical material. Ramensky wrote that, although the allocation of boundaries is possible, they are conditional a priori. In phytocenology and geobotany, the organismic concept dominated until 1960. The results of the studies by Whittaker (1956, 1960) in the Central Appalachians convincingly confirmed the ideas by Ramensky and Gleason. Nearly the entire world scientific community of geobotanists very quickly recognized the individualistic concept and, accordingly, the continuity of the vegetation cover, almost completely denying the feasibility of the organismic concept. The truth of the individualistic concept under certain implementation conditions was rigorously proven within the framework of the mathematical theory of stability and was confirmed in direct field studies using various statistical methods of ordination (Puzachenko, 2004). However, at the end of the 20th and beginning of the 21st century, the absolute generality of the individualistic concept was questioned (Puzachenko, 2017). This, in particular, led to a new surge of interest in boundaries and integrity and the study of their nature.

† Deceased.

Similar problems of the correlation between integrity and continuity exist in soil science and landscape science; however, they are less developed. For example, in soil science, pedon is understood as a material body with linear dimensions from one to ten meters; however, the majority of soil scientists consider the soil cover as a whole or in its individual properties as continuous. In landscape science, Armand (1975) proved the continuity of the landscape and the conditionality of the distinguished boundaries. On the other hand, the school of landscape science, which inherits ideas from Solntsev, does not express any doubts about the objectivity of their existence. It should be noted that the practice of planning of the use of natural resources requires the mandatory introduction of territorial units with their boundaries.

Let us pay attention to the fact that individualistic and organismic relationships in a real system are quite compatible. The individualistic concept by condition reflects the equilibrium (stationary) relationships between the elements of the system. Statistical methods by themselves, used for multivariate correlation analysis, distinguish only the equilibrium relationships. The contribution of these relationships can be estimated by the coefficient of determination of the variation in space of the value of each element from the axes or factors identified in the multivariate analysis. However, if the coefficient of determination is very high, this does not mean that the relationships are in equilibrium and that there are no organism-like formations that disturb it. To confirm equilibrium, it is necessary that the residuals from the statistical model of each element have a strictly normal distribution and zero autocorrelation of the series. Usually this is not observed, and there are intervals in space that have at least four neighboring points with one sign of deviation from the equilibrium model (Puzachenko, 2017). It is worth noting that the problem of identification of boundaries and their reality is also considered when analyzing the spatial structure of populations (Ranke et al., 2021), in economic geography (Gallaway, 2005; Kolosov et al., 2014), and in other areas somehow relating to phenomena that have spatial differentiation.

In this article, on the basis of information theory (and the Kotelnikov fundamental sampling theorem, in particular), we propose a methodology for distinguishing and describing the boundaries of natural objects as a function of the sampling frequency in a space series with a regular sampling step. It is proposed to introduce for space the measurement unit “berg”—one complete oscillation per kilometer, which is essentially identical to the unit “hertz” for the time series. Four main models of the appearance of boundaries (and, in the particular case, of integrity) arising from the theory of nonlinear dynamic systems are considered briefly. The main provisions of the methodology are illustrated by real measurements of the properties of biogeocenoses and measurements of reflected solar radiation in the SPOT 6 satellite channels. In the proposed formulation of the problem, general theoretical notions of nonequilibrium, nonlinear, dynamic systems closely interact with the notions of a classical naturalist, combining them to answer the fundamental questions as to why specific spatial and temporal structures exist and what the ways of their evolution are. In answering these questions, we are looking for the physical mechanisms that generate them, consistently improving the corresponding models.

INFORMATION THEORY IN THE STUDY OF TRANSITION ZONES

In considering the formulation of the problem of boundaries in landscape ecology, an almost complete disregard of the well-developed and, in its foundations, strictly proven theory of information transmission in time through communication channels of any physical nature can be noted (Shannon, 1949). Fluctuation frequencies of variables of any physical nature are measured on a continuous scale with a unit of measurement of one complete oscillation per second (hertz), which ensures their complete continuity and commensurability. It must be assumed that the same is true for spatial fluctuations. Accordingly, our task is to show the correlation of uncertainty in distinguishing sharp and gradual boundaries with the frequency band implemented in specific measurements and to propose a method for its reduction for real studies of the structure of transition zones and identification of possibly complete systems with sharp boundaries. However, the theoretical basis for studying the spatial structure based on transects with a regular sampling interval and remote information with a given maximum resolution is common.

In information theory, general information transfer laws are formulated that are valid for systems of any physical implementation (Shannon, 1963). In the general case, it is assumed that there is a transmitter (in a broad sense, a medium) that generates oscillations of all its properties over time or, in other words, behaves as a dynamic system. The receiver in this case is a researcher who, with the aid of some measuring system, attempts to reproduce the variation of individual properties. Naturally, for each property, there is a specific receiver that reproduces the signal coming from the environment at regular intervals. In view of this, a question arises as to what these equal intervals should be and what the time of receiving information should be in order to completely, without distortion, reproduce the function that reflects the behavior of the considered property in time. This problem was solved by V.A. Kotelnikov (1933). Now it is called the sampling theorem and underlies the law of communication channel capacity by K. Shannon (Shannon, 1949).

The sampling theorem proves the following statements. (1) If the function does not contain frequencies higher than W Hz, it is completely determined by its instantaneous values at times separated by 1/(2W) s from one another. (2) The function is completely determined by its instantaneous values if it does not contain frequencies below W_1 Hz and above W_2 Hz. (3) The function is completely determined by its instantaneous values if it requires transmission with a length of less than T conventional units with a frequency of $f_{\min} < 2/T$ and a step (distance) between samples $n\Delta t$ ($f_{\max} = 1/2n\Delta t$), at $n = 1$ (each successive sample) $f_{\max} = 0.5$ (Nyquist frequency). For any oscillations of any variables in time, a single unit of frequency measurement—hertz, or one oscillation per second—is introduced. In this case, samples can be taken at steps of 1 s, 0.1 s, or any other time step. The theorem states that a function is completely reproducible from observations if it does not contain frequencies higher than a certain value and, accordingly, is not reproducible if it contains them at samples separated from each other by the minimum time interval possible in a given measurement system. The second entry of the theorem defines the reproducibility of the functions in the W_2–W_1 frequency band. The third entry represents time in dimensionless units, with the minimum frequency being determined by the measurement time and the maximum frequency being determined by a doubled regular interval. When the interval is equal to one step in arbitrary units, then the frequency is maximum and equal to 0.5. This dimensionless form is commonly used in all statistical packages of time series analysis. It should be noted that the introduction of the common unit of frequency "hertz" makes it possible to compare any measurements performed in time.

In the transition to space series, all provisions about the external variable reproducible in measurements remain the same and the whole powerful theory of time series analysis is fully applicable to the analysis of space series. In systems for measuring reflected solar radiation from satellites, the minimum spatial frequency is set by the pixel size, and the maximum frequency is set by half of the series length along the corresponding coordinate. As in the case of time, for space we can introduce frequency in conventional units. However, this is inconvenient, since it hampers comparing independent measurements performed at different sampling steps or at different resolutions of satellite images. In general, the possibility of applying the sampling theorem to space series was shown by Puzachenko (1976, 1983). He suggested measuring the diversity of all landscape properties on transects with a regular sampling interval and proposed a unit of spatial frequency "berg," which is equal to one full oscillation per kilometer. Thus, for example, if we say that the oscillation frequency is 100 berg, this means that, on average, one hundred oscillations are reproducible per kilometer (if, of course, such oscillations do exist). The selection of the surname of L.S. Berg for the name of the unit for is obvious to Russian-speaking geographers, and the selection of 1 km as a unit corresponds to the idea that the landscape in the understanding of the school of N.A. Solntsev should not have smaller linear dimensions. The idea of a strictly linear transect with a regular sampling step was fully implemented in the study of the landscape diversity of small islands in the southwestern Pacific Ocean (Puzachenko, 1994).

Let us consider the possibility of identifying the type of boundaries using the sampling theorem on two simple model examples (Fig. 1). Let us set the measurement interval according to a regular scheme with a length of twenty points. The distance or time in this case is given in conventional units. A sharp boundary (face) is set in Fig. 1a, and a gradual boundary is set in Fig. 1b. Let us show how the model series is approximated at different frequency bands (i.e., testing step). The first frequency in this series is $f_1 = 0.05$, and the step (distance) between samples is $n = 1/2f$, i.e., ten points of a given row. As follows from Fig. 1, at this frequency, the entire given region is reflected as a continuum boundary. Set the next frequency $f_2 \leq 0.2$, which corresponds to a distance of 2.5 points. The given boundary model is described practically by a sinusoid. At $f < 0.45$, the step between samples is 1.111, and at $f < 0.5$ measurements are performed at each point, and the given sharp boundary is described almost completely (Fig. 1a). In Fig. 1b, similar calculations are given for a gradual boundary. As follows from this figure, at the maximum sampling frequency we obtain an accurate description of the transition zone. Thus, if we study some boundary region of some property in nature, then a constant increase in the "steepness" of the approximating line with increasing sampling frequency indicates the existence of a sharp boundary. Otherwise, at the maximum sampling frequency, the transition zone is clearly distinguished.

Another, definitely more convenient, method for identifying the type of boundary can be proposed. Consider the square of the distance of the values of a variable between adjacent currents through two, three, four, etc., points, simulating a change in the measurement step of variable $D_{i=1,2,3,\ldots n\text{–step}} = (y_i^2 - y_{i+k}^2)^2$. As follows from Fig. 2, if the boundary at the maximum measurement frequency is discrete, then at different measurement steps it will give the same distance value, shifting only along the X axis by one step (Fig. 2a). If the boundary is gradual (Fig. 2b), then, in calculations for neighboring measurement points, we obtain a gradual change in distance. As the step changes, the distances become more contrasted, and when measuring through four points, the boundary becomes sharp with the only reliable distance. Thus, we find that a sharp boundary at one measurement frequency can be transient with an increase in frequency; it is impossible to prove formally that the boundary is sharp at all possible measurement intervals in time or space. Thus, when measuring real objects, it is always necessary to specify for which frequency we obtain a sharp boundary.

Obviously, we will obtain the same results if we consider the values of the variable at different sam-

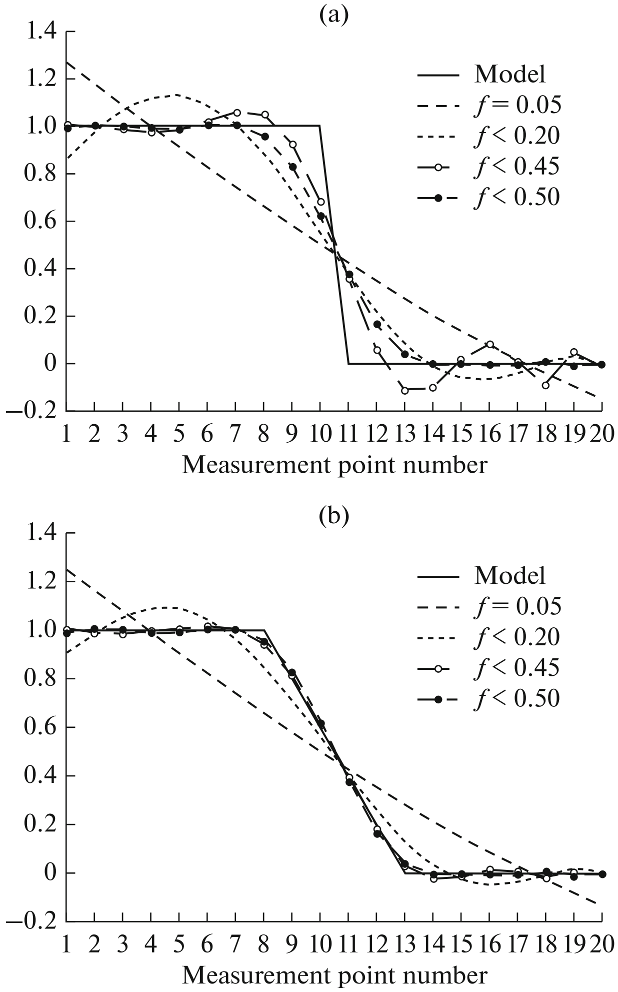


Fig. 1. Representation of the boundary structure for two models through a continuous Fourier function: (a) sharp, (b) gradual.

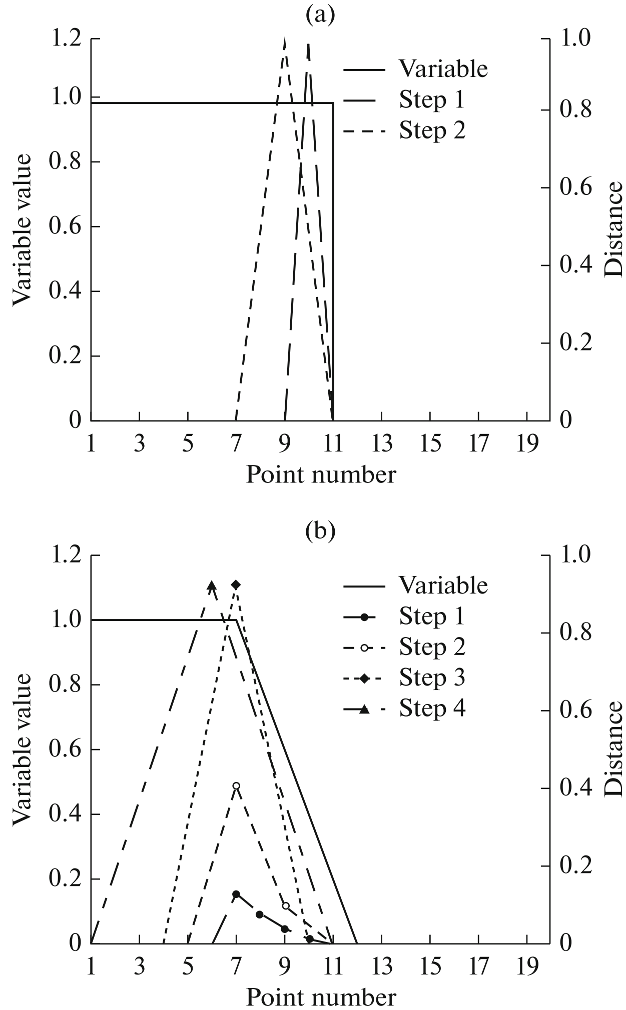


Fig. 2. Representation the boundary structure for two models through changes in the sampling step: (a) sharp, (b) gradual.

pling steps for averaged values over two, three, four, etc. points, rather than for individual points. This, in particular, is more convenient when working with remote information. To ensure the comparability of different independent measurements performed on different scales, let us proceed to spatial frequencies (berg). If our observations are carried out at 1-m steps, then the maximum frequency will be 500 bergs, or five hundred complete oscillations per km. Based on this relation, it is easy to convert the calculations performed in arbitrary units into a unit of spatial frequency.

CLASSICAL MODELS THAT GENERATE DIFFERENT TYPES OF BOUNDARIES AND THE FORMATION OF INTEGRAL NATURAL SYSTEMS

Distinguishing different types of boundaries is of little interest if it does not search for an answer to the question of the mechanisms that generate them. In the general case, it is obvious that, in most cases, the boundaries distinguish the areas of nonequilibrium transformations of geosystems in space. Of particular interest are natural systems limited by sharp boundaries. Possibly, they distinguish holistic organism-like formations, which, by the condition, have an increased stability in a wide range of changes in environmental conditions. At first glance, it may seem that it is difficult to identify the genesis of boundaries; however, the theory of nonlinear dynamics offers a strictly limited list, and for each model, criteria for their identification in nature can be proposed.

Bifurcation model. Many relationships in nature are described by models of the second or third degree:

$$Y = (a_{\max} - X)^{\lambda}(X - a_{\min})^{\beta},$$

where X is an external variable, $a_{\max}$ and $a_{\min}$ are the left and right boundaries of the domain of existence of Y, and α and β are coefficients describing asymmetric parabolas (Kuznetsov, 1998).

Such a model usually describes the ecological niches of species by one factor (X) of the environment (Puzachenko, 1996). This model often explains well the transitional zones of different structures between plant communities. The main condition for their implementation is a gradual change in environmental conditions, usually on an inclined surface of the relief, which determines the gradient of moisture and mineral nutrition. The boundary can be sharper when parent rocks change. We mean that each species depends on four or five external factors, rather than one, each of which has its own potential bifurcation points. According to the continuum model, species can be independent of each other; however, if in some species the bifurcation points by some factor are close, then they are simultaneously replaced by analogues that ecologically replace them along the gradient. Accordingly, there will be a transition zone in the region of close bifurcation points. If there is some competition between species, then the boundary can be sharp. The study of this type of boundary requires a multidimensional analysis of species relationships to some virtual factors and display of their changes along the environment gradient (Puzachenko, 2004). If the statistical model of the mutual distribution of species on the transect, obtained on this basis, generates the observed transition zones, then the bifurcation mechanism can be considered proven. The bifurcation mechanism describes many processes in nature: a sharp change in soil moisture with a change in slope steepness, geochemical barriers, etc.

Hysteresis model. Hysteresis describes the movement of some variable along different trajectories as the value of the factor that determines it increases and decreases (Scheffer et al., 2001; Visintin, 2006; Beisner et al., 2008). Suppose there is a steppe in some area at the moment t_0. Let there be a gradual increase in precipitation, and a forest forms in the place of the steppe. Suppose that a new climate cycle has begun and the amount of precipitation is gradually decreasing. However, the forest will not transform along the same trajectory. It can transform abruptly to the steppe if the amount of precipitation is significantly less than it was at the moment t_0. Let us give a real example of the hysteresis that arose before our eyes on the territory of the Central Forest Reserve (observations made in 1994–2017). Throughout the entire observation period, a general trend of winter warming is observed (Shuiskaya, 2021). Before our eyes, the proportion of maple, linden, and elm in spruce forests on the moraine, as well as the proportion of hazel in the shrub layer, increased (Pukinskaya, 2020). However, the spruce forest still remained a spruce forest. In 1996, as a result of a windfall, the spruce forest was destroyed over a large area (Puzachenko, 2007). The summer air temperature over the wind-fallen trees is 2–3 degrees higher than that over the spruce forest. As a result, the forest renewed through broad-leaved species (first of all, through linden, maple, and elm). The closeness of the canopy is so high that the spruce in the renewal occurs singly. At the same time, the spruce forests that were not affected by the windfall remain spruce forests and the boundary between them and the broad-leaved forests is almost always sharp. Hysteresis is widespread in nature. To prove this mechanism of occurrence of a sharp boundary, a direct or indirect analysis of climate change in the study area is usually required.

Reaction–diffusion equation with Turing flow. The simplest version of the model is based on the classical population dynamics model:

$$dx/dt = rx(1 - bx),$$

where x is a variable, r is the multiplication factor (activator), and b is the self-inhibition factor (inhibitor).

Let us supplement the model with a space in which diffusion of the inhibitor and activator occurs. Spatial structures, including those with sharp boundaries, arise depending on the ratio between the diffusion coefficients of the inhibitor and activator. In the general case, if the diffusion coefficient of the inhibitor is significantly greater than the diffusion coefficient of the activator, spatial structures appear (Turing, 1952; Riznichenko, 2003). This model, for example, describes well the formation of discrete patches and bands of vegetation in a semiarid climate (Tian, 2015). It will probably describe spatial structures in podzolic soils with a frequency of approximately 1000–500 berg. The model generates a hierarchical organization with correctly repeating spatial frequency bands. The potential feasibility of this model can be identified on the basis of spectral and wavelet analysis, within which hierarchical levels with multiple frequencies will be established. Although the possibility of implementing this model in the vegetation cover in a temperate climate is problematic, its feasibility cannot be ruled out. Possibly, it is implemented in meadows with different ratios of the distribution coefficients and the action of the diffusion coefficients of inhibitors as a reflection of the competition of species in space. The feasibility of this model for the tree layer is highly questionable.

A model based on positive feedback. Due to positive feedback, parts of a system mutually reinforce each other. If such a system is not limited by the environment and is linear, then the system is absolutely unstable, and this autocatalytic reaction will lead to an explosion (Armand, 1988). However, in the "animals–plants–soil" system, the relationships are usually nonlinear, and the environment determines the permissible area of existence. There are many examples of such systems. A typical example is a raised bog formed on the basis of a positive "peat–sphagnum mosses" feedback. The same relationship exists between the forest and the steppe, first of all, due to positive feedback between forest and precipitation and positive feedback between meadow (steppe) vegetation and soils. Under certain climatic conditions and certain terrain conditions (usually southern exposures), secondary meadows are quite stable in the forest zone as well. Apparently, there are similar formations in natural forests. The problem of identifying and studying such integral systems is that they can be fully manifested only in old forests that have never been cut or burned. Such forests occur very rarely and are of great value in this regard. Forest systems built on the basis of positive feedback are a priori nonequilibrium and have their own mechanisms that increase their stability. Their study is of great importance, as it provides a basis for constructing models of the formation of integrity in plant communities and biogeocenoses. The criterion for distinguishing such systems is the sharpness and almost complete closure of boundaries. If we have obtained such formations on the basis of multispectral remote information analysis, they should be the subject of a special study aimed at identifying specific mechanisms for maintaining integrity and, ideally, at modeling them.

In fact, the four models considered exhaust the possible mechanisms of emergence of transition zones and boundaries. The limited nature of this list makes the search for the mechanisms that explain the formation of different variants of transition zones quite realistic.

EXAMPLES OF ANALYSIS OF THE STRUCTURE OF TRANSITION ZONES ON REAL OBJECTS

Assessment of the boundary structure by soil density. Figure 3 shows a transect with a step of 20 m crossing the moraine ridge in the Central Forest Biosphere Reserve (the maximum position of the lake of the Valdai glaciation, which, apparently, was supported from the south by a glacier). Sandy lacustrine deposits with an average thickness of 50–60 cm cover the entire surface from the west. From the east, there are sabulous loamy lacustrine deposits on the slope of the moraine ridge. In the central, lowest part of the transect (point –3), at a depth of 4 m, the Mikulino peat deposits are exposed, which are underlain by sapropel and lacustrine clays. Peat deposits of the Mikulino age are also exposed on the ledge (points 14 to 24) at a depth of 4 m. From point 7 to point 25, there is a mixed-age bilberry–sphagnum spruce forest of the fourth quality grade on peat–gley soils with an average peat thickness of 50 (maximum 70) cm approximately 4000 years old.

Buried spruce trunks are found in peat. It can be postulated that the age of this unique biogeocenosis is calculated in millennia. This superstability is the result of a positive feedback loop in the spruce–sphagnum–peat system. Spruce with a relatively sparse canopy (closeness 0.5–0.6) provides the necessary illumination for *Sphagnum girgensohnii* Russ. and *Sphagnum angustifolium* Russ. The formation of a peat horizon with poor mineral nutrition determines the development of a strong root system of the spruce, which makes it resistant to the windfalls that periodically destroy spruce forests on adjacent moraine hills. The sphagnum cover does not prevent the successful regeneration of spruce in the windows formed as a result of destruction of single old (about 250 years old) spruce trees. Direct measurements of the CO_2 balance showed that the biogeocenosis releases CO_2 in dry years; the opposite situation is observed in wet years (Milyukova et al., 2002). As a result, only 50 cm of peat have accumulated over 4000 years. The spruce forest considered is an unconditional example of a holistic biogeocenosis (ecosystem). From the zero point to point 6 on the transect, a typical forest sphagnum bog is situated, which is sharply separated from the spruce forest. The width of the boundary is 1–2 m. The convex shape of the surface is determined by the more intensive growth of sphagnum in the central part of the bog. The transition from the forest bog to the small-leaved spruce forest is gradual. The proportion of pine gradually decreases. The bog is definitely advancing, since two spruce trees that grew at its boundary near the zero point 25 years ago dried up in approximately 1993 (E.S. Shaposhnikov, oral communication). Figure 4a shows the spatial variation in the soil density on a mini-transect with a sampling step of 1 m at the boundary of a sphagnum spruce forest and a windfall site (indicated by numeral 2 in Fig. 3). Figure 4b shows the modern topography and the topography without the organogenic horizon (initial topography). The soil density was determined from the samples taken with a drill (Robur, Volta, Russia) with a step of 4 cm at a depth of up to 40 cm. Soil is formed on lacustrine sands overlain by a thin layer of mantle loam. A moraine (most likely of the Moscow glaciation) was exposed at a depth of 1 m at point no. 41. Figure 4b shows the modern surface and the surface without the organic horizon; to distinguish sharp boundaries, the quadratic normalized Euclidean distance is calculated for the entire profile up to a depth of 40 cm with a step of 4 cm:

$$D_{i,i+1} = \sum_{j=1}^{10} \left(\frac{x_i^j - x_{i+1}^j}{x_i^j + x_{i+1}^j} \right)^2,$$

where x is the soil density, i is the point number, and j is the number of the soil layer, which can rightfully be called the “boundary thickness.”

Figure 4b clearly shows how the advancement of the sphagnum spruce forest, as a result of the accumulation of peat, levels out the initial topography; however, it apparently occurs step by step. Four powerful sharp integral density boundaries can be distinguished at a frequency of 500 berg. The maximum thickness of the boundary was measured at point 23. Figure 5 shows the change in soil density for three selected characteristic horizons: 4, 12, and 32 cm. Apparently, the boundaries at the considered frequency for all three horizons are sharp but correspond to different

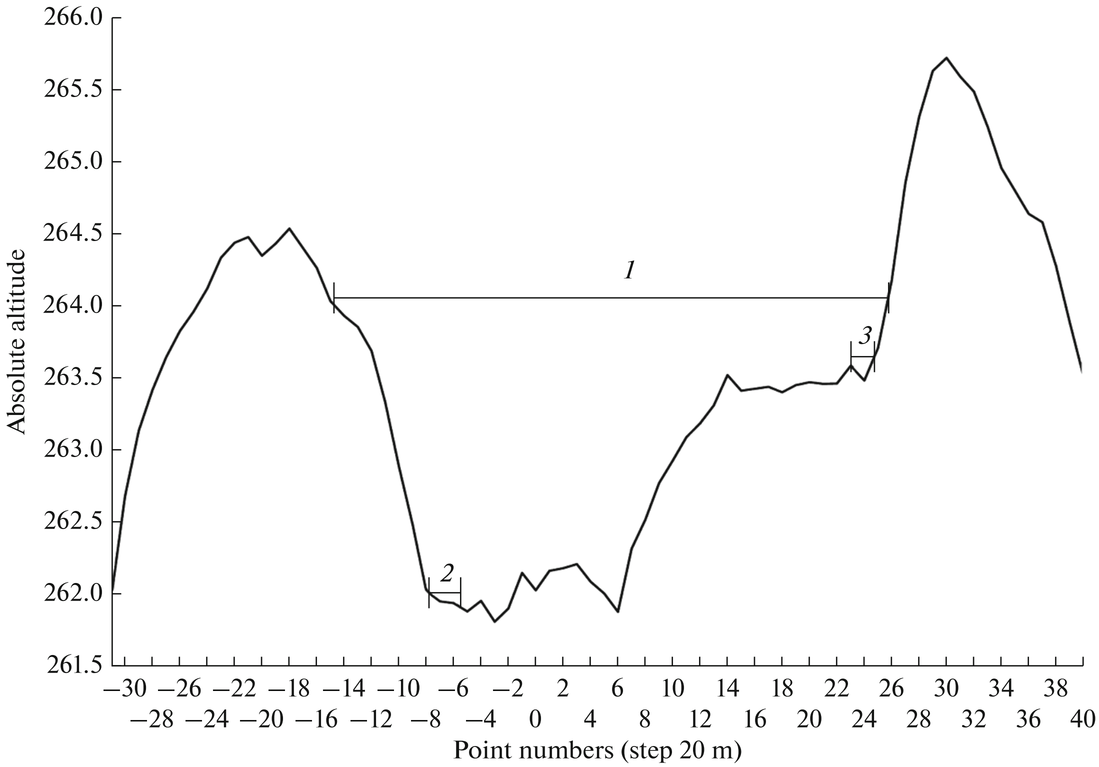


Fig. 3. Transect across the moraine ridge in the Central Forest Reserve. (*1*) Maximum position of the surface of the Valdai glaciation lake. (*2*) Mini-transect at the boundary of a sphagnum spruce forest and a 1996 windfall site in the place of a broad-leaved spruce forest on pale podzolic soils. (*3*) A mini-transect at the transition from the boundary zone of a raised bog to a small-leaved spruce forest on pale-podzolic soils.

points of the transect. It can be assumed that, in this case, sharp boundaries can be explained by a model with positive feedback between the sphagnum and the peat formed by it, and the presence of several boundaries can be associated with cyclic climate change: peat actively accumulates in wet periods and ceases to accumulate in dry periods. This, in particular, is confirmed by the active growth of sphagnum bogs in the last twenty wet years (Puzachenko et al., 2014). The distinguished sharp boundaries are valid for a frequency of 500 berg. At a higher frequency (e.g., 5000 berg, sampling at 10-cm intervals), they may turn out to be transient. Apparently, this can be verified by sampling at an appropriate frequency. Ideally, the realism of the model will be proved if the sharp boundary for the upper horizon, on average, corresponds to the radial advancement of sphagnum for one year.

On the eastern part of the main transect, a second mini-transect was laid with a sampling step of 1 m (indicated by numeral 3 in Fig. 3) to study the boundary in the transition zone from peaty–gleyic soils with an almost surface position of groundwater to typical pale–podzolic soils with their deeper position. Soils are formed on fine-grained lacustrine sands. Figure 6 shows the spatial variation in relative humidity along the mini-transect upon the transition from the boundary zone of the raised bog to the small-leaved spruce forest. From points 1 to 15 on the mini-transect, the tree layer with a sum of cross-sectional areas of 20 m^2/ha is formed by spruce (85%) and birch (15%). Then, to point 30, the tree layer is formed by spruce, aspen, and birch with a density of about 0.5. The herbaceous layer is sparse and formed mainly by sedges. Sphagnum mosses are absent. This sharp transition is clearly seen in Fig. 6: from points 1 to 13, the relative humidity of the soil at the surface is more than 90%, and then it quickly decreases to 70%. Further, starting from point 30, the sum of cross-sectional areas increases to 23 m^2/ha, and the forest stand is already dominated by birch (26% spruce, 69% birch, and 5% aspen). Then, to the end of the transect, the forest stand is dominated by aspen (59%) with codomination by birch (26%) and spruce (15%), with the sum of cross-sectional areas of 27 m^2/ha. Grass and moss cover change along the transect as follows: up to point 6, the moss cover consists of sphagnum mosses with a projective cover of up to 90% and single blueberries. In contrast to the first mini-transect, where sphagnum was under optimal conditions and had a green part height of 10 cm, sphagnum on the second mini-transect was oppressed and had a green part height of no more than 3 cm. This state of sphagnum is explained by the adverse impact of the fairly thick leaf litter, which excludes its active vegetation in late

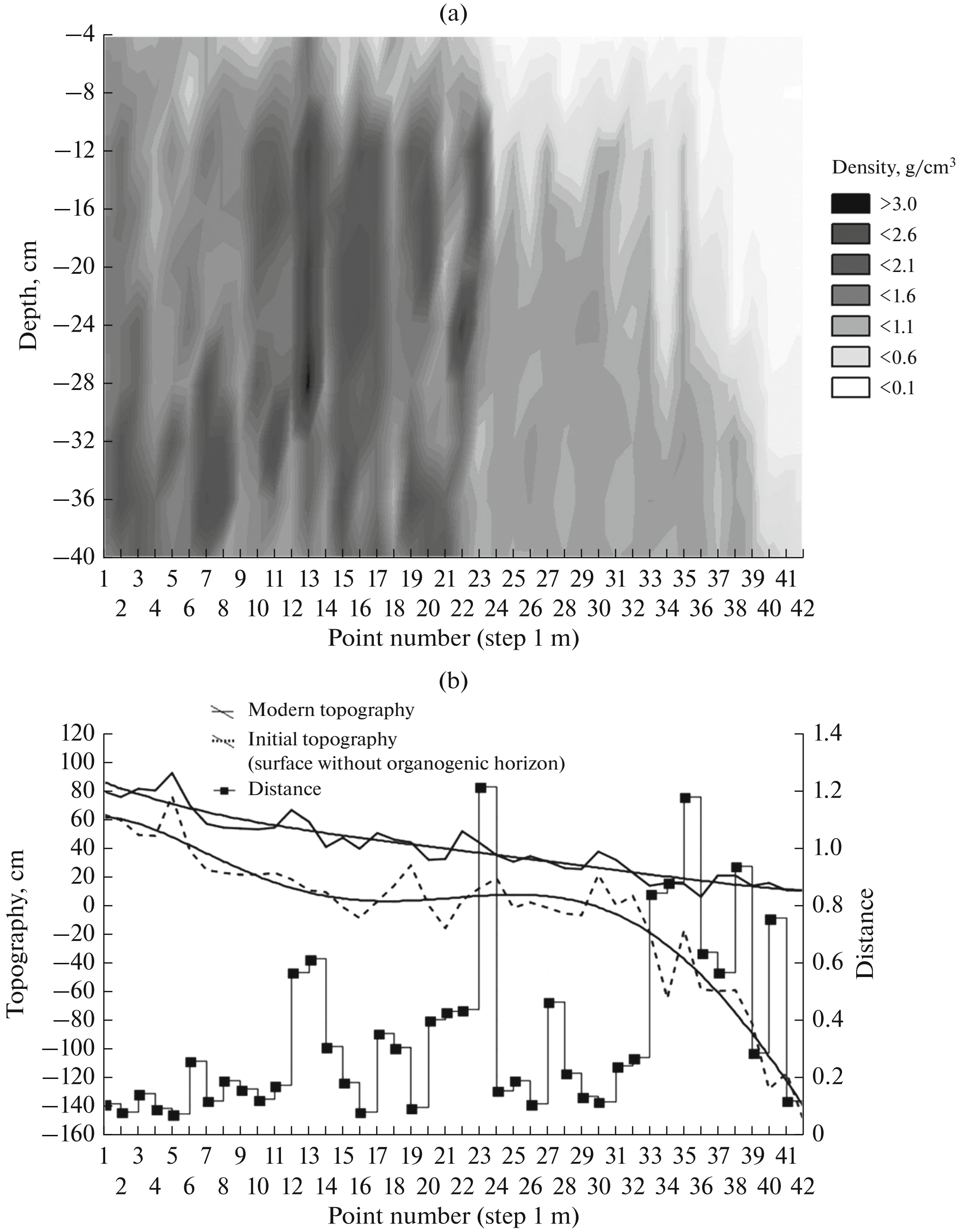


Fig. 4. Variation in soil properties on the mini-transect 1: (a) spatial variation in soil density; (b) initial topography, modern topography, and the distance between adjacent points according to soil density.

spring and early summer. At points from 7 to 13, the projective cover of sphagnum decreases to 50%, and at points from 13 to 16 it decreases to 10–20%. Further along the mini-transect, there is a more or less uniform grass cover with a projective cover of up to 20%, which consists of typical boreal species (blueberries, chickweed, and ferns).

Figure 7a shows the spatial variation in the soil density on the second mini-transect, and Fig. 7b shows the topography and Euclidean distance by soil density. As follows from Fig. 7b, the modern surface is almost flat, whereas the initial topography shows a slight rise from west to east, which is now completely leveled by the accumulated peat mass. The fact that a boundary zone is formed within this mini-transect is obvious; however, this zone has a very complex internal structure: sharp boundaries of different thicknesses are fixed at points 2, 6, 8, 10, 20, and 23 (Fig. 7b). The boundary would be sharp and single if the measurements were performed with a step of 20–

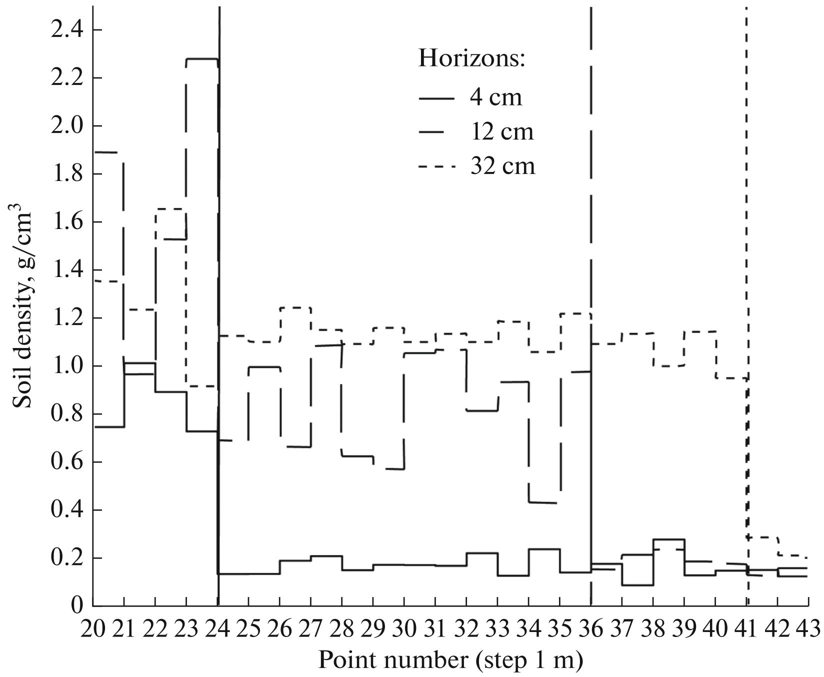


Fig. 5. Distinguishing sharp boundaries by soil density for three characteristic horizons.

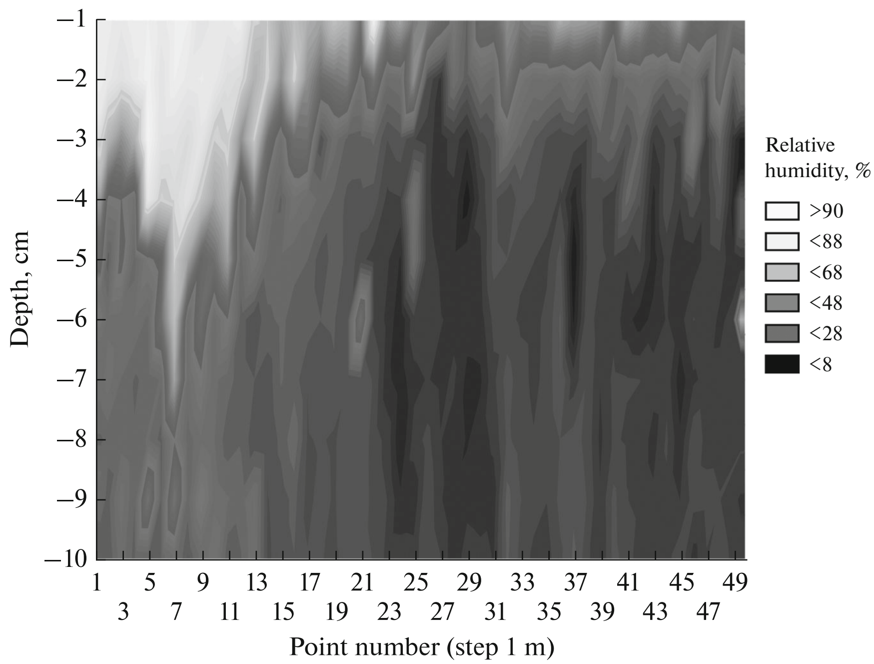


Fig. 6. Spatial variation of the relative soil moisture on the mini-transect 2.

25 m (i.e., at a frequency of 25–20 berg). Obviously, the peat horizon is formed according to the low-land type of bogging, and the thin sphagnum layer has no significant effect when the mineralization of organic material is blocked by its high humidity at a very high water capacity. Apparently, sphagnum colonizes the surface already prepared by this process. It can be assumed that the advancement of the lowland bog is based, on the one hand, on a positive feedback mechanism and, on the other hand, on bifurcation mechanisms that switch the system abruptly from the state of "well decomposing organic matter" to the state of "weakly decomposing organic matter." In this case, the governing parameter moves to the bifurcation

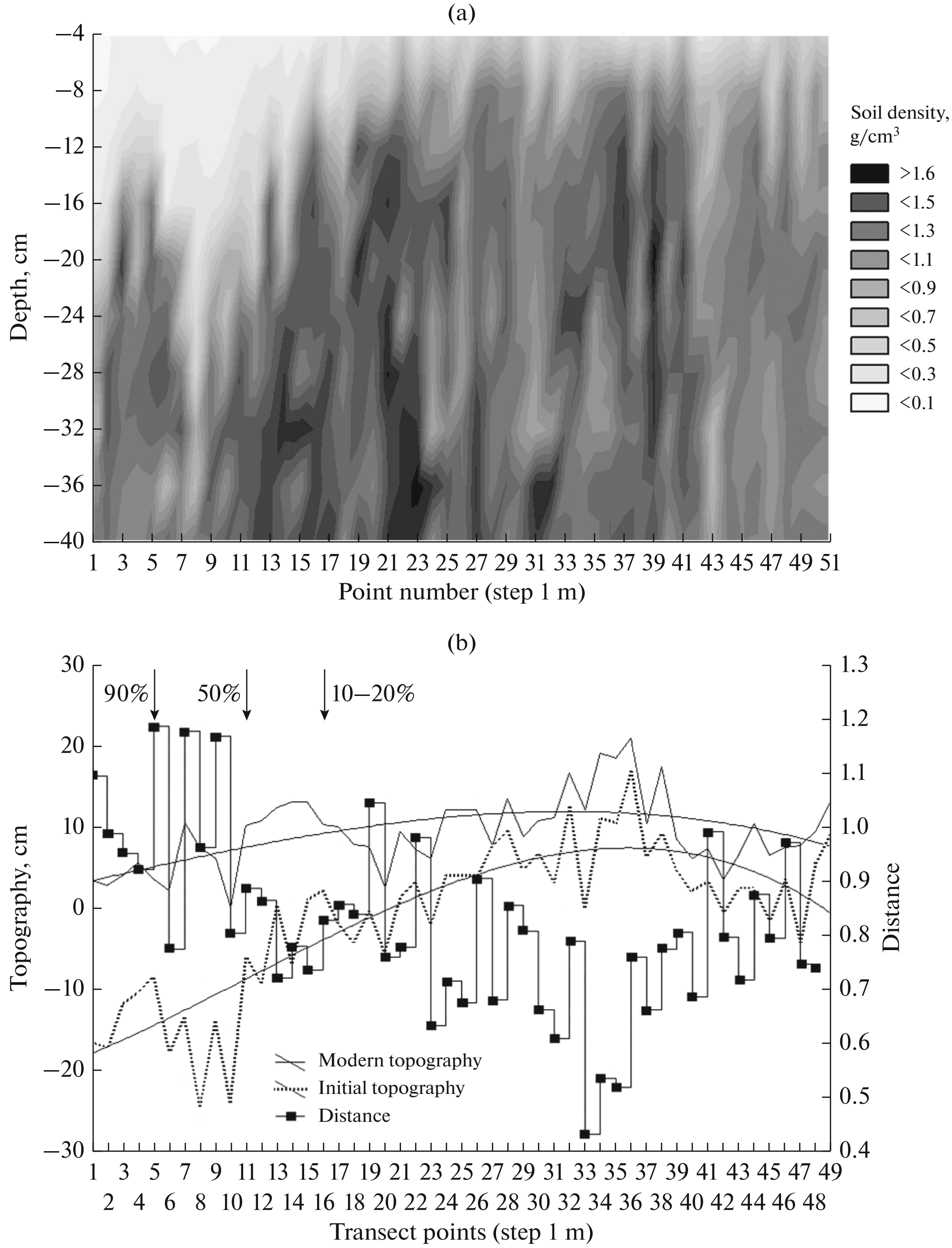


Fig. 7. Variation in soil properties on the mini-transect 2: (a) spatial variation in soil density; (b) initial topography, modern topography, and the distance between adjacent points according to soil density.

point due to self-development based on positive feedback. As a result, the process in general is abrupt, with the formation of a series of sharp boundaries. Of course, in the cases considered, the mechanisms explaining the appearance of sharp boundaries can be regarded only as hypothetical.

Ideally, for each case, a rigorous mathematical model that reproduces reality should be built. However, even the first level of qualitative analysis of the possible mechanisms for the formation of sharp boundaries seems useful. The two examples demonstrate the possibility of studying the formation of sharp boundaries in the soil. In principle, by analogy, such studies can be organized for soil and vegetation together. However, before proceeding to the study of details, it is necessary to identify the position of the sharp boundaries and the transition zones for the entire territory on the basis of multispectral remote information.

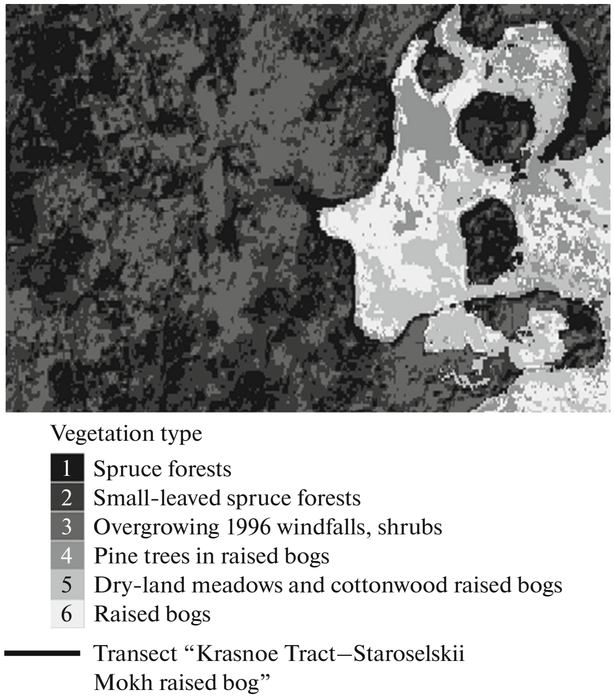


Fig. 8. Map of the vegetation cover of an area of the Central Forest Reserve. Classification according to SPOT 6 multispectral survey (spatial resolution 6 × 6 m in pixel) for a frequency of 83.3 berg.

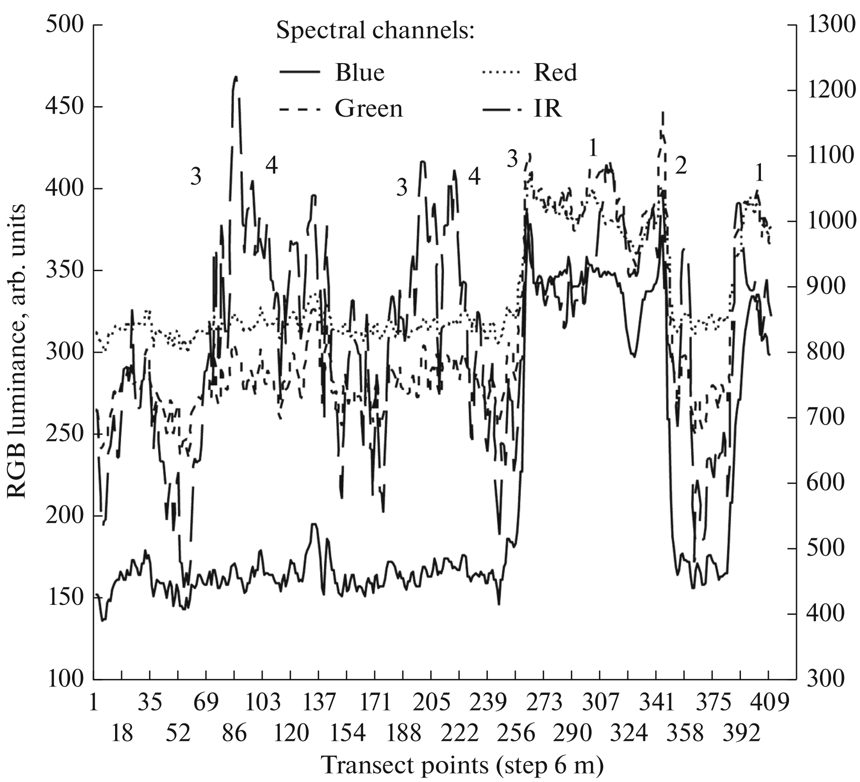


Fig. 9. Variation in brightness in four channels along the transect: (1) raised bog, (2) moraine hill with an old spruce forest, (3) spruce forest, (4) 1964 windfall.

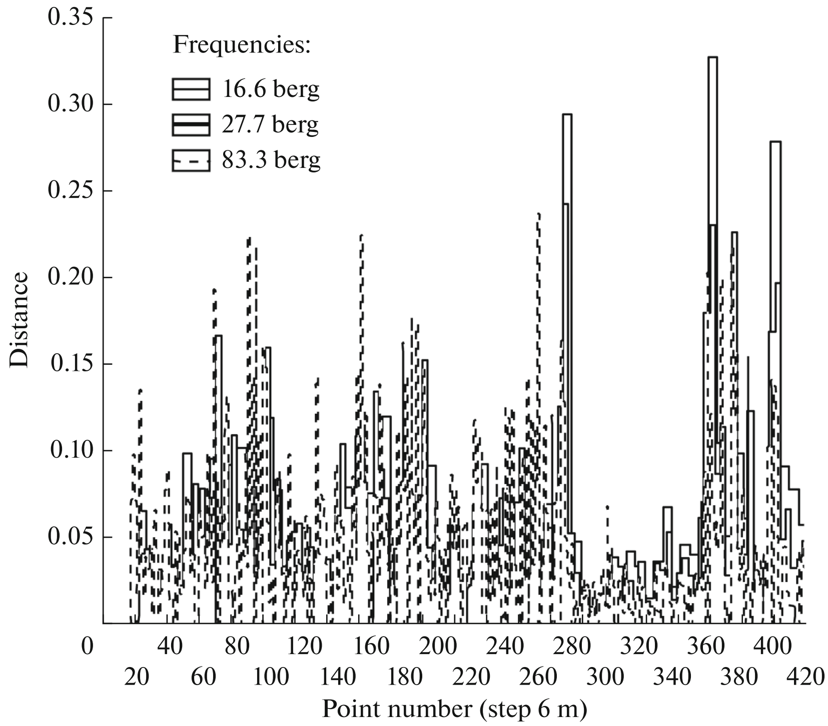


Fig. 10. Boundaries on the transect (distances are given by brightness for different frequencies).

Distinguishing boundaries on the basis of multispectral remote information. Figure 8 shows the area chosen for demonstrating the representation of boundaries on the basis of multispectral distance information.

Figure 9 shows changes in brightness in four spectral channels along the transect in the initial spatial frequency (6-m survey spatial resolution). The transect crosses the raised bog, spruce forests, and windfall sites.

Figure 10 shows the normalized Euclidian distance, which marks the sharp boundaries for three frequencies (83.3, 27.7, and 16.6 berg), calculated from the data for four survey channels between adjacent points with a given frequency, i.e.,

$$D = \sqrt{\left(b1x_i - b1x_{i+1}\right)^2 + \left(b2x_i - b2x_{i+1}\right)^2 + \left(b3x_i - b3x_{i+1}\right)^2 + \left(b4x_i - b4x_{i+1}\right)^2},$$

where $b1x_i$ is the first spectral channel of the ith point of the transect and $b2x_i$ is the second channel, etc.

The comparison of the distances in these three frequencies demonstrates the dependence of the representation of sharp boundaries on frequency. For example, the sharp boundary of the raised bog is distinguished at all frequencies. On the other hand, the sharp boundary in the bog itself is distinguished at a frequency of 83.3 berg, and the second one is distinguished at a frequency of 16.6 berg and disappears at higher frequencies. The boundary between the spruce forest and windfall sites is clearly distinguished at low frequencies and is partially preserved at high frequencies. At a high frequency, within the limits of both the spruce forest and the windfall sites, sharp boundaries appear, which disappear at a low-frequency representation. Thus, using multispectral representations and considering them at different frequencies, we get the opportunity to study the internal structure of the transition zones.

Figure 11 shows the high-frequency and low-frequency boundaries for the area of interest (Fig. 8). The boundary was defined as the maximum of three directions along which the Euclidean metric was estimated relative to the central point of the 3 × 3 convolution kernel, going from the upper left corner of the image to the right one line by line: from north to south, from northwest to southeast, and from west to east. The expression for the floating square can be written as follows:

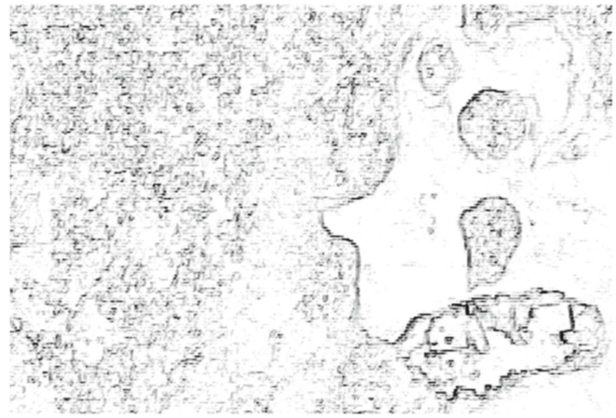
$$D = \max\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d\left(x_{i,j}, x_{i+1,j}\right) \\ 0 & d\left(x_{i,j}, x_{i,j+1}\right) & d\left(x_{i,j}, x_{i+1,j+1}\right) \end{pmatrix},$$

where $d(x_{ij}, x)$ is the Euclidean distance between the central point of the kernel in the original image and the adjacent point in the direction specified by the *ij* coordinates.

Obviously, at a low frequency, the diversity of boundaries is much lower than at a high frequency. In fact, bogs, the transitional zone between a bog and a kame, and a fragment on a kame with two land-use variants are distinguished unambiguously. Other boundaries are very fragmentary. At a high frequency, boundaries on raised bogs distinguishing their different variants appear. Often closed boundaries of different contrast are distinguished in the forest area. Apparently, in all cases, the frequency band of the boundaries can be measured and, if necessary, their internal structure displayed in multispectral measurements. The possibilities of distinguishing boundaries by remote measurements form the basis for their direct study in the field.

Methods for the study of boundaries and integrity in nature. The individualistic community model reflects the equilibrium relationships between species, whereas the organismic model reflects the nonequilibrium ones. Both models are simultaneously implemented in the system. The boundaries distinguished on the basis of multispectral measurements from space a priori demonstrate the areas of imbalance, and study of them helps to understand the mechanisms that generate them. In fact, they contain information about the organization of the system as a whole. Naturally, a lot of boundaries are distinguished on the basis of remote information and a random choice in their study is not productive. Obviously, it is sufficient to consider them for the following combinations of external variables: (1) old forests and windfalls—young and secondary forests in general; (2) even surfaces—slopes; and (3) loams—sands. Thus, we obtain eight basic combinations, which, taking into account four or five repetitions, is 30–40 points. This, of course, is the minimum from which a study can be started. Practice has shown that the boundaries distinguished using SPOT 6 remote information are almost always identified well on the ground in the interval of 6–12 m. For a rapid analysis of the boundary, we lay a 30- to 40-m transect orthogonal to the boundary with 1-m leveling. Using a high-resolution panoramic digital camera, we photograph the vegetation on both sides of the boundary. The quality of digital photographs makes it possible to distinguish tree species accurately and count their number. Ten meters from the boundary to the left and right, we lay standard geobotanical plots and photograph the crowns with a camera equipped with a Fish-Eye lens to assess the leaf surface index. At each point of the transect, we photograph the grass cover on a 1 × 1 m plot and measure soil moisture at depths of 20 and 10 cm using a TDR-300 moisture meter (Field Scout, United States). The quality of the photograph usually allows the identification of species and their projective cover. We drill the soil to a depth of 2 m with a step of 5 m to determine whether the soil formation conditions are homogeneous and whether the boundary is a consequence of a change in the mechanical composition of the soil. In case of suspicion that the boundary is determined by a change in the mechanical composition, we intensify drilling in the boundary area. As a result, in the first approximation, we can establish whether the boundary is determined by external factors (an inflection of the topography, its gradual change, or a change in soil-forming rocks) and assess whether it is a change in the functioning of vegetation, which possibly determines the bifurcation. If the external variables remain unchanged, then the boundary is most likely determined by positive feedback between individuals of the same species, usually with root renewal (for example, aspen) and positive correlations in the grass layer between species, including the renewal of trees and shrubs. Thus, already at the first stage, we can systematize the types of boundaries by their possible genesis on the basis of a rapid description and then proceed to a detailed study of the mechanisms that generate them at selected points. Naturally, with the development of this study, addi-

(a)



(b)

Fig. 11. Boundaries at frequencies of (a) 83.3 berg and (b) 16.6 berg.

tional analysis of especially characteristic, closed boundaries will be required.

CONCLUSIONS

The development of the ideas considered in this article requires the development of appropriate theoretical and methodological substantiations and adequate methods of field research, as well as the use of remote information and new methods of data analysis. No less important is the change in the paradigm, which in this case is reduced to the notion of landscape as a nonlinear, nonequilibrium dynamic system and that the main information about the mechanisms that determine the dynamics and evolution of the system is concentrated in the area of imbalance. This implies the development of basic knowledge of the theory of dynamic systems and new technologies. At the same time, the formulation of the problem and its general theoretical and methodological foundations seem to us necessary already now. We hope that some of the techniques demonstrated in this work can be used in research today.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflicts of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

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