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Geography and Natural Resources 29 (2008) 267–272

GEOGRAPHY
AND NATURAL
RESOURCES

Methods to identify geosystems with a commonalty of intercomponent relationships

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Received 6 February 2007

Abstract

We estimate the effectiveness of several methods of identifying different-scale functionally integral mosaic geosystems interconnected by a common type of intercomponent relationships by considering an example of relief – vegetation system. The form of the function is used to reveal the physical process that is responsible for the spatial differentiation. A comparison is made of the informational content and the limitations of using multi-regression equations, information measures of connection, nonparametric correlation coefficients, and the Jacobi determinant.

Keywords: geosystem, scale, intercomponent relationships, process, multi-regression equation, information measure of connection, Jacobi determinant.

Introduction

Planning of nature management usually involves a need to correctly determine its spatial and temporal scales within which the particular types of relationships between natural bodies can manifest themselves. There is a great variety of challenging issues related to understanding the relationship between the scales of natural processes. Firstly, it is the problem of the difference between the regional scale of decision-making in the field of nature management and the local (point) scale of collection of data on the structure and functioning of landscapes [1]. Secondly, hierarchical organization of nature requires taking into account the processes that are realized not only at a level under investigation but also, as a minimum, at two adjacent levels, of which the upper level is determined by the constants of the process, and the lower level is engendered by its mechanisms [2-4]. Thirdly, on the same territory and at the same time there are taking place processes with different characteristic times, for each of which there exists its own specific hierarchy [5]. Fourth, a self-similarity of the processes at different hierarchical levels, and also a change of the leading factor at the passage to another level can manifest itself in nature. And, fifth, there is a problem of discriminating between the contributions from the factors operating at different hierarchical levels, into variation of the variable analyzed.

Because of the different characteristic times, a change in the properties of vertical structure does not always proceed in a concerted fashion with a change of the main factor of spatial organization. Therefore, upon determining the main factor of spatial organization, it is appropriate to assess its connections with different properties of landscape components. Within a geosystem with a unified type of intercomponent relationships the response of a landscape component to quantitative changes of the leading factor must be expressed by functions out of the same class with similar parameters. If such a system is identified on a territory, then it is possible to represent from the form of the function the physical process that is responsible for spatial differentiation.

The objective of this paper is to compare the validity of several methods of identifying functionally integral geosystems interconnected via a unified type of intercomponent relationships by using the relief – vegetation system as an example.

Materials and methods of investigation

This paper is based on using the data of field investigations made in the southern part of the Arkhangelsk region, in the subzone of the middle taiga, as well as on the digital model of the relief at a scale of 1:50 000, and the space-acquired Landsat 7 image (June 2001). As a result of converting the values of spectral brightnesses of the channels of the satellite image, several independent factors of differentiation of vegetation cover were identified [6], one of which was interpreted from field data as the manifestation

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doi:10.1016/j.gnr.2008.09.012

of the response of vegetation cover to a variation in moisture content of the habitat. This factor was used in the analysis (hereinafter referred to as the moisture content factor), as it is independent of the anthropogenesis, whereas the other factors reflect anthropogenic changes: the relationship of the forest and field areas, and coniferous and small-leaved species. The highest factorial values correspond to stows of high cottongrass-sphagnum bogs with sparse pinewood and spruce-pine sphagnum forest on peaty-podzolic soils, and the lowest values correspond to the most well-drained stows: foxberry green-moss (lichen in some places) pine forests on podzolic soils, and to mesophyte blackberry-cat's tail-fescue meadows on soddy-calcareous soils of steep native slopes of the valleys.

The digital model for the relief, generated with the use of the (ArcView3.2a) GIS, and an original program for analyzing raster images – FRACDIM [6] were employed for calculating the indices of the degree of drainage of the relief: the degree of vertical dissection (standard deviation of heights in a square of side 2000 m), the degree of horizontal dissection (the sum of the lengths of water streams in an identical square), the grade, the degree of curvature, and the distance to the nearest talwegs. The satellite image and the digital model of the relief were brought to the same resolution with the pixel size of 400 m, which is comparable with the mean size of the stows identified on the landscape map of the study area. Five terrains are identifiable on the plot under investigation [7].

A general approach, suggested in this paper, implies calculating the parameters of connections between landscape components (represented by GIS layers) in the moving square where the data set is formed by all pixels surrounding the central pixel in the specified field, and the computational result is assigned to the central pixel. In doing this, we gain insight into the variation of the type and strength of the connections across space and identify functionally integral geosystems with identical contributions made by independent variables (characteristics of the relief in this case) to the state of the dependent variable (the properties of vegetation that are sensitive to hygrotope). By comparing the results of calculations when the size of the moving square is changing, it is possible to reveal a characteristic scale of manifestation o the intercomponent relationships. From here on, by the variation in scale is meant a change in the size of the moving square. Another aspect of the problem, i.e. the dependence of results on resolution (pixel size) deserves further investigation.

As one of the methods to assess the functional integrity of geosystems, the technique is suggested for calculating the values of the functional determinant of a special form (the Jacobi determinant, or Jacobian) composed by partial derivatives of the functions analyzed in space variables [8]. In the presence of a functional connection the Jacobian goes to zero in the vicinity of the point selected. It is suggested that an estimate of the elements of the functional determinant for a certain area be represented by the values of the coefficients in the equations of planes tangent to the given dependencies constructed from points of an elementary square of side 2n+1 pixels by the least square technique. The value of the Jacobian is assigned to the central pixel of the elementary square, which explains the oddness of its side. By shifting the center of the square from one point of space to another, it is possible to obtain estimates of the Jacobian for all pixels of the region except for the boundary pixels. This will result in obtaining the map indicating the areas in which there can exist a functional dependence between parameters.

The question of the dimension of the square is of particular importance. The estimation of the partial derivatives is the more accurate, the smaller is the square. Also, the resulting plane will nearer to the tangent. An increase in the size of the square leads to a smoothing of the random component as well as contributing to the transition to another hierarchical level of organization of the territory. Thus the use of the Ja-

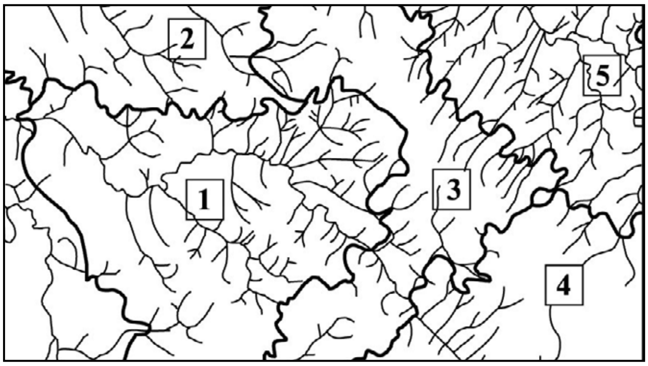

Fig. 1. Landscape structure and hydrographic network of the study area (level of terrains).

Terrains: 1 – Rostovskaya – strongly dissected structural-erosional, well drained plain composed by Perm marls with the superimposed mantle of lacustrine-glacial Valdai and morainic Moscow deposits with agricultural lands and secondary spruce-birch-pine forests on agrosoddy-podzolic soils in the interfluves, and combinations of agroabrazems and rendzinas on the slopes; 2 – Mostnitskaya – weakly dissected undulating lacustrine-glacial weakly drained plain composed by thin layers of Valdai sands and loamy sands underlain by Perm marls with secondary spruce-birch-pine forests on podzolic soils, by oxylomesophytic meadows on agrosoddy-podzolic soils, and by small high bogs on peatlands soils and peaty-gley soils; 3 – Gridinskaya – weakly dissected stepped erosional-morainic weakly drained plain composed by relatively thick layers of Moscow morainic sandy loams with a mantle of lacustrine-glacial deposits underlain y Perm marls, with spruce-aspen-birch and spruce-birch-pine forests on peaty-podzolic-gley soils, combined with high and transitional bogs on peatlands and peaty-gley soils; 4 – Bolvanskaya – weakly dissected morainic gently-oblique weakly drained plain composed by relatively thick layers of Moscow morainic loamy sands with a mantle of lacustrine-glacial deposits, with spruce and spruce-aspen-birch forests on podzolic illuvial-ferruginous soils and peaty-podzolic-gley soils, combined with high and transitional bogs on thick peat layers; 5 – Sodenskaya – strongly dissected structural-morainic-erosional well drained plain composed by Perm marls, overlain by a thin mantle of Moscow lacustrine-glacial and morainic deposits with secondary spruce-birch-pine forests and agricultural lands on agrosoddy-podzolic soils, agroabrazems and rendzinas.

cobian makes it possible to establish to a first approximation the presence of a functional connection between landscape components; yet, this does not provide information on the form and strength of this connection.

In the case where it is necessary to determine the strength of connection and where information on its sign can be neglected, it is permissible to invoke the second method based on calculating Shennon's diversity indices. The information measure of connection is insensitive to data biases from a normal distribution, and to the nonlinearity of connections, which differs it to advantage from parametric methods of statistical analysis. On the other hand, it does not make it possible to determine the sign of connection. By analogy with the measure of information transmitted by a set of channels, the measure of interconnection can be estimated as

$$I(X_1, X_2) = \sum_{j=1}^{j=N} H_j(X_1, X_2) - H_0(X_1, X_2)\,,$$

where N is the number of variables analyzed (layers, and landscape c); X_1, X_2 are the coordinates of the center of the moving square; H_j is the diversity index for a separate layer ($j = 1,2,\ldots N$), and H_0 is the diversity index for all layers. When the parameters are independent, the value of the measure of connection will be zero, i.e. $I = 0$. In the presence of a connection, the value of its strength will be increasing ($I > 0$) with an increase in the measure of connection. Here the connection is interpreted as the decrease of the number of combinations of values of parameters realized across the territory.

Since a calculation of Shennon's diversity indices uses not the values of the parameters themselves but the occurrence frequencies of their values, there is a need for the procedure of quantifying and replacing the discrete values by the number of a natural series from 1 to M, where M is the number of groups. In the subsequent discussion we use uniform quantization of all layers. This naturally brings up the question as to the fractionality of quantization. In the case of a small number of groups, each subregion can be rather large, so that in calculating the value of H_j the number of variants for a qualitative description of the system will be insufficient. In the case of a large number of groups the number of variants can exceed considerably the size of the region under investigation, let alone the moving square. This induces us to suggest that in most cases the variants of combinations of quantified values of parameters, realized in each of the moving squares, will be different (the diversity index H_0 approaches its maximum value).

To verify this hypothesis, a computational experiment was conducted. To do this, the measure of connection was estimated between three parameters (horizontal and vertical dissection, and moisture content factor) for different values of $M = 2^i$ ($i = 1, 2, \ldots 8$) for the moving square 5x5 pixels in size (Fig. 2, a). The criterion of the best choice of the number of groups, we believe, can be represented by the value of M^*, at which a maximum of the function $\Delta I(M)$ is attained. Selection of such a number of groups guarantees a maximum

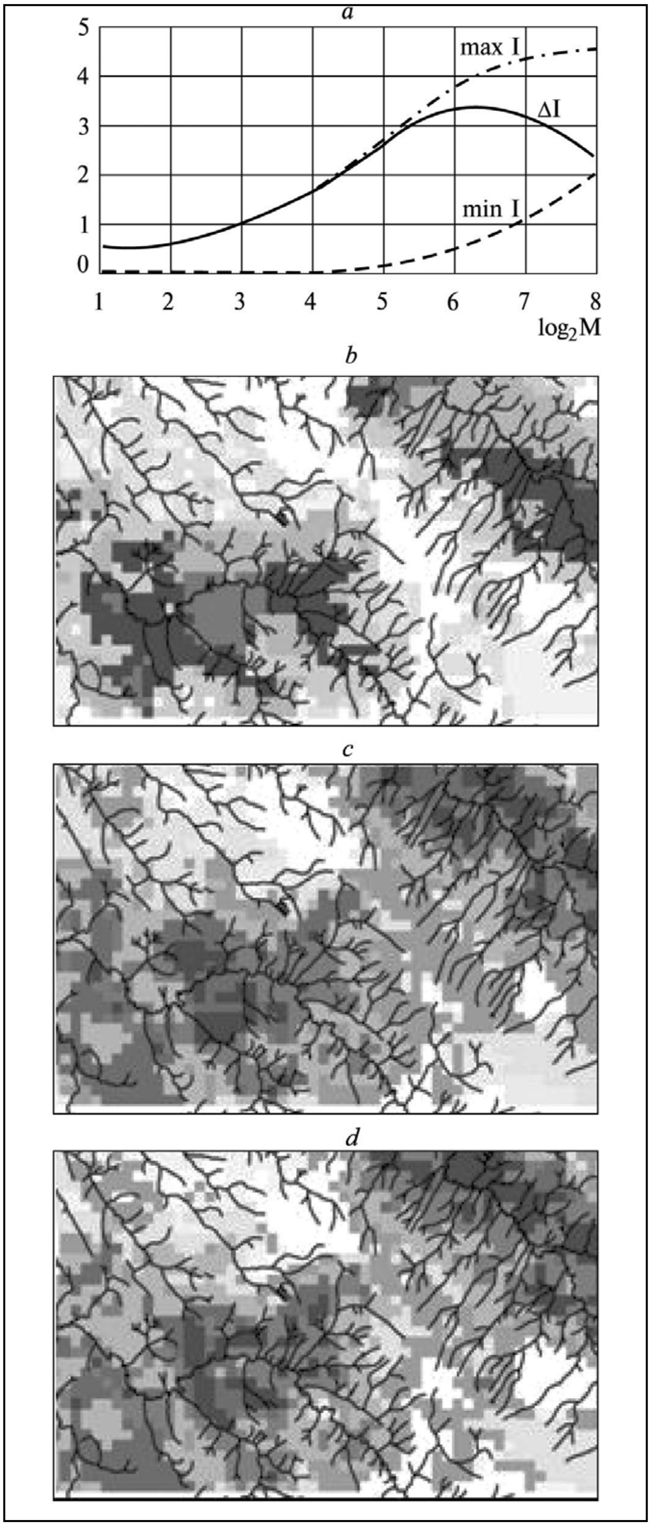

Fig. 2. Selecting the optimum level of quantifying the variables for calculating the information measure of connection between the moisture content factors and vertical dissection of the relief.
a – information measure of connection: Min I – minimum values, Max I – maximum value, ΔI = Max I – Min I; b – classification of the territory (8 classes) from th set of information measures of connection in the moving square of side 2000 m, with the fractionality of quantization of variables: 16 gradations; c – same, 64 gradations; d – same, 128 gradations.

range of variation of the measure of connection of the parameters. Comparison of the results for spatial distribution of the types of intercomponent relationships in the relief – vegetation system, with a different fractionality of quantization of variables (see Fig. 2, b-d) shows that the results are the most stable for weakly dissected territories: flat and convex interfluves with shallow catchment declivities. Within densely dissected terrains, when the fractionality of quantization is changed, it is highly probable that the conceptual interpretation of the classes of relationships will be altered. Comparison of them with the real landscape structure of the territory reveals that in the case of an intermediate fractionality of quantization (see Fig. 2, c) functionally unified territories are in a regular interrelationship with the location of the boundaries of terrains. This correspondence is not (and must not be) a strict one; however, there are clearly identifiable groups of stows undergoing the influence of bog massifs, a dense network of drained water streams, deeply incised expanded stretches of the valleys, flat interfluves, and so on.

The third method of spatial analysis of intercomponent connections involves constructing a multi-regression dependence. An elementary square in this algorithm plays the role of a linear vicinity, which removes the possible questions as to the need to use nonlinear connections. A change of the coefficients in the multiple regression equation (the parameters of the equation) shows a succession of the processes occurring in the region of space under investigation as well as estimates the strength of connection between landscape characteristics. The advantage of the technique of spatial representation of intercomponent connections in terms of multi-regression equations implies that it is possible not only to estimate the strength of connections from the coefficient of determination but also to compare in modulus and sign the contribution from separate factors (independent variables) to the variation of the dependent variable. A classification of objects from values of standardized coefficients of the regression equation by the k-mans method makes it possible to identify mosaic geosystems which are unified in the main factor of differentiation.

The fourth method is used, if the linearity of the relationships between the characteristics of landscape components is questionable. The tool of analysis is provided by parametric correlation coefficients. Unlike the regression equations, this method cannot be used to integrally estimate the extent to which a dependent variable is described by a set of independent variables. However, a classification of objects from the set of values of correlation coefficients of the dependent variable with each of the independent variables can also be used to determine across space the boundaries of geosystems with a unified type of intercomponent relationships.

Discussion

The conceptual interpretation of the classes of relationships in the relief – vegetation system is exemplified by a calculation o the strength and sign of connections using the nonparametric Spearman correlation coefficient between values of the moisture content factor, on the one hand, and each of the five drainage characteristics, on the other. Each pixel is assigned the value of Spearman's coefficient obtained for the vicinity 2000x2000 m size, which roughly corresponds to the stow level of landscape diversity.

All stow-pixels are combined into eight classes according to the values of the five correlation coefficients (see the table). Classes of relationships 1 and 2 differ only in modulus but not in the sign of the coefficient, as they characterize a different degree of manifestation of the same process. Moisture content increases in the case of small vertical and horizontal dissection, and small grades at a large distance from drained water streams. These two classes characterize the runoff formation process at the edge of watershed bog massifs, with a decrease in humidification of the stows as the stagnant water regime changes for the running water regime.

Class 3 characterizes the process of concentration of the runoff and enhancement of moisture content in the bottoms of the valleys. Class 4 reflects an increase of moisture content from convex weakly dissected interfluves to the bottoms of the valleys, which corresponds to the process of transition of the slope runoff to a state of moisture stagnation n floodplains. Class 5 corresponds to an increase in humidification on steep convex weakly dissected slopes as a result of the process of sheet unloading of groundwater at the contact of morainic loams and native Perm marls on the slopes. Class 6 differs from the preceding one by the sign of connection with horizontal dissection, which corresponds to outcrops of groundwater not on even slopes but in gullies dissecting steep slopes. For class 7, moisture content increases within concave bottoms of the valleys near strongly meandering rivers and in places of their confluence. Class 8 occurs on territories in deeply incised valleys with a dense network of tributaries. Moisture content increases here in the zones of fragmentation and outcrops of bedrock on the surface of steep slopes.

Mean values of Spearman's rank correlation coefficients for classes of connection of the moisture content factor with drainage indices

Class of relationships	Vertical dissection	Horizontal dissection	Distance to talweg	Grade	Degree of curvature
1	-0.17	-0.35	0.08	-0.11	-0.16
2	-0.57	-0.52	0.27	-0.46	-0.20
3	-0.43	0.31	0.04	-0.36	0.08
4	-0.31	-0.14	-0.16	-0.25	0.24
5	0.29	-0.28	-0.03	0.20	-0.10
6	0.21	0.14	0.06	0.20	-0.25
7	0.01	0.21	-0.18	0.01	0.23
8	0.37	0.38	-0.23	0.35	0.22

The same procedure was applied in carrying out the conceptual interpretation of the classes of relationships obtained by a classification of standardized coefficients of the regression equation [9] as well as of the Jacobian determinant and information measures of connection (with due regard for the above imitations of each of the last two methods).

Of interest for a classification of the territory are only those classes in which the Jacobians approach zero nearly for all pairs of variables. These are classes in which, with high probability, there exists a functional connection between the moisture content factor and each of drainage characteristics. Classes revealed are 2 or 3, depending on the vicinity of calculation. Spatial distribution o classes makes it possible to divide territories with the most characteristic relationships of a particular scale. Connections of a landscape scale (a square of side 6800 m) encompass almost the entire territory, while the centers of functionally connected territories occur in the Gridinskaya and Mostnitskaya terrains (Fig. 3, c). Nevertheless, this does not mean that the form of a connection is identical throughout the territory.

The areas of stability of the form of linear relationships invariant to the scale, determined by the method of classification of the coefficients of the regression equation, largely coincide wit the areas of a functional connection determined from the Jacobians at a stow scale as well as at a landscape scale (see Fig. 3, a, b). An interesting feature was detected for the Zayachya and Sodenga interfluves in the analysis of the areas of classes identified from Spearman's coefficients at different scales. For squares of side 2000, 3600 and 5200 m the connection has the same form as in a classification of the regression coefficients. If, however, a calculation is performed at a landscape scale in a square of side 6800 m, then there appears a difference between the signs of the coefficients of moisture content connection with vertical dissection. Furthermore, the coefficient of determination of the linear equation decreases abruptly with a change of the vicinity of a calculation from 5200 m to 6800 m. This strongly suggests that in this area: 1) a functional connection of moisture content with the relief does exist; 2) this connection has a linear character over the range of scale from stow to terrain (for squares of sides from 2000 to 5200 m), and 3) it is reasonable to suppose that there occurs a change of the form of connection to a nonlinear form at a landscape scale (for a square of side 6800 m).

When the areas of classes of relationships having high values of the information measures coincide with the areas of high values of the coefficient of determination of the regression equation, there are grounds to believe that a reliable connection of the linear type does exist. If, however, the information measure shows a presence of a connection, and the coefficient of determination is low, then there is more likely a deviation of the connection from linearity.

For a landscape scale (a square of side 6800 m used in calculations) it was established that in the study stretch along the right bank (the Zayachya and Sodenga interfluve) there is a reasonably high agreement between the areas of classes with high values of the information measures of connection and the high values of the coefficients of determination $R^2>0.2$ (see Fig. 3). Furthermore, the substantive interpretation of the classes of relationships identified by using the information and regression methods is largely consistent. Clearly identifiable are the territories with no relationships,

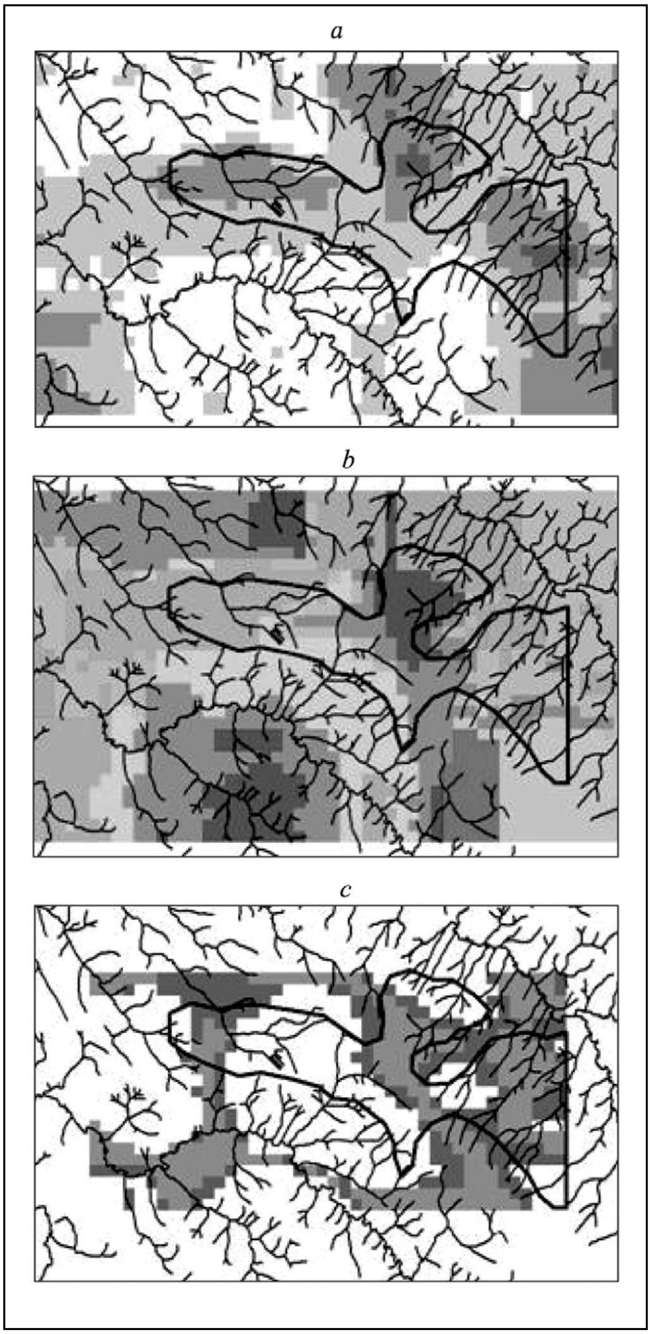

Fig. 3. Relationship of the range of classes with high values of information measures of connection (heavy line) at a landscape scale (the moving square of side 6800 m).

a – with the range of high values of the determination coefficients of the linear regression equation; b – with the ranges of classes of linear relationships from the regression model; c – with the areas of classes of relationships from the Jacobians.

both from the information measure and from the coefficients of determination of the regression equations along the Zayachya valley, and along its left bank. On the other hand, the Mostnitskaya terrain near the node of contact of differently directed lineaments on the interfluve includes a stretch for which the values of the information measure of connection are high, but the values of the Jacobians of pair relationships show the absence of the information measure. In such a case, it seems more reasonable to rely on the information measure of connection which is insensitive to sharply peaked values of variables within the square.

A most serious difference arises form a comparison of the areas of connections identified by the information method and from the Jacobian at a stow scale. While the information measures show a presence of a connection in strongly dissected terrains, a functional connection is absent there according to the Jacobian; on the contrary, however, it is pronounced on weakly dissected interfluves. Thus the information measures largely confirm the results obtained by the regression methods, although they reduce their reliable area, but they are in disagreement with results from calculating the connections using the Jacobian. Conceivably, such a difference is accounted for by the differing accuracy of estimating the partial derivatives forming part of the Jacobian. On territories where a change in parameters is taking place relatively slowly and smoothly (small grades of relief, and weak dissection), the values of partial derivatives are estimated to a higher accuracy when compared with places in which an abrupt change in parameters occurs (abrupt transitions from flat to step-slope stows).

As pointed out above, the estimates of partial derivatives are calculated on a discrete set of spatial variables. The use of different scales makes it possible to bring the accuracies of estimation closer together and contributes to improving the final results of employing the Jacobi determinant in the analysis of the interrelationships of the parameters. Not only does the method suggested by A. K. Cherkashin [8] for estimating the presence of interrelationships for three parameters with the use of the Eulerian condition have all the disadvantages which arise when calculating the Jacobian, but it narrows the relationships estimated to a class of homogeneous functions. (A homogeneous function is the function $F(x_1,x_2,\ldots x_n)$ satisfying the condition: there exists such a real number β, the homogeneity index, that at any α the equality $F(\alpha x_1,\alpha x_2,\ldots \alpha x_n) = \alpha^\beta F(x_1,x_2,\ldots x_n)$ holds.

Conclusions

The study reported in this paper leads us to suggest that, firstly, the most encouraging possibilities of identifying functionally integral geosystems with a unified type of intercomponent relationships are provided by multi-regression modeling which can be verified by a nonparametric correlation, the information measures, and the Jacobi determinants. Secondly, the result from identifying functionally integral geosystems via the information measures of connection depends on the fractionality of quantization of variables. Thirdly, the applicability of the Jacobi determinant for identifying functionally integral geosystems is confined to territories with a smooth change in parameters, and to the impossibility of seeking interrelationships for more than two parameters. And, fourth, comparison of results from identifying functionally integral geosystems using parametric and nonparametric methods at several scales makes it possible to reveal hierarchical levels of landscape organization at which there arises a nonlinear component of intercomponent relationships.

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