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LANDSCAPE METRICS FROM THE POINT OF VIEW OF MATHEMATICAL LANDSCAPE MORPHOLOGY

ABSTRACT. This paper discusses potential of obtaining answers to key issues related to the use of landscape metrics by applying approaches of mathematical landscape morphology. Mathematical landscape morphology that has emerged in Russia's geography in recent years serves as the basis of the new scientific direction in landscape science. Mathematical landscape morphology deals with quantitative regularities of the development of landscape patterns and methods of mathematical analysis.

The results of the research conducted have demonstrated that landscape metrics are subjected to stochastic laws specific to genetic types of territories; furthermore, these laws may be derived through mathematical analysis. It has been also shown that the informational value of different landscape metrics differs and can be predicted. Finally, some landscape metrics, based on the values derived from single observations, nevertheless allow one to provide assessment of dynamic parameters of existing processes; thus, the volume of repeated monitoring observations could be reduced. Other metrics do not posses this characteristic. All results have been obtained by applying mathematical landscape modeling.

KEY WORDS: landscape metrics, mathematical landscape morphology, landscape pattern, mathematical models.

INTRODUCTION

Nowadays, quantitative parameters that characterize landscape mosaics formed at the Earth's surface are widely used [Vinogradov, 1966; Nikolayev, 1978; Victorov, 1966, 1998; Leitao, et al., 2006; Riitters, et al., 1995, etc.] These parameters are called landscape metrics; earlier in the Russian literature, terms "quantitative indicators of landscape structure of the territory" were used [Ivashutin and Nikolayev, 1969; Nikolayev, 1975; etc.]. Currently, a large number of such parameters exist both in literature [Victorov, 1998; Leitao, et al., 2006] and in software tools for analysis of mosaics [McGarigal, et al., 2002; Pshenichnikov, 2003]. Furthermore, the number of possible metrics is infinite. Finding new metrics is precisely the direction that the efforts of many researchers are focused.

Landscape metrics are used in a variety of geographic tasks – in landscape analysis and planning, definition of geological conditions, analysis of changes in the environment, risk assessment, and in other areas [Nikolaev, 1975; Leitao, et al., 2006; Riitters, et al., 1995; Victorov, 2005a, b; Moser, et al., 2007; etc.]. At the same time, undertaken studies have omitted a number of important issues related to landscape metrics. These are:

- Are the values of landscape metrics subjected to any laws and can we predict them?

- What is the relative informational value of different landscape metrics and of their combinations?
- To what extent do landscape metrics reflect the dynamics of landscape structure of the territory?

The answers to these questions are crucial because they determine the effectiveness of landscape metrics in addressing problems of landscape planning, of defining geological conditions, and of environmental monitoring.

RESEARCH METHODS

The modern level of landscape science provides solution to these issues on the exact theoretical basis. Mathematical landscape morphology that has emerged in Russia's geography in recent years serves as the basis of the new scientific direction in landscape science [Victorov, 1998, 2006; Victorov and Trapeznikova, 2000; Kapralova, 2007]. Mathematical landscape morphology deals with quantitative regularities of the development of landscape patterns and methods of mathematical analysis. The object of study is a landscape pattern (morphological structure), i.e., the spatial mosaic formed on the surface by the areas corresponding to the natural-territorial complexes developed in this territory.

One of the main outcomes of the mathematical landscape morphology is mathematical models of landscape patterns [Victorov, 1998, 2006]. A mathematical model of a landscape pattern based on existing models is the theory of stochastic processes and is a collection of mathematical relationships that reflect the landscape's most important geometric properties. A special role is played by the so-called canonical mathematical models of landscape patterns. The canonical mathematical models of the morphological structures of a particular genetic type are the mathematical models of the morphological structures formed under the impact of one process under homogeneous physiographic conditions, i.e., the models of simple landscape patterns. The requirement of uniformity includes absence, in the area, of faults, buried hollows, abrupt changes in chemical composition of surface sediments, etc., but at the same time does not limit composition and amount of rainfall, temperature, etc. Thus, a canonical mathematical model of morphological structures represents such elements that can be used to create a mathematical model of a landscape pattern anywhere. For example, to date, there have been established canonical mathematical models of morphological structures of alluvial plains, of plains with the development of karst, of subsidence-suffusion processes, of erosion plains, etc. [Victorov, 2006].

The method of mathematical landscape morphology is based on the fact that equations of mathematical models are valid for the same genetic type of landscape in a very wide range of physical and geographical conditions (composition of deposits, sediments, age, etc.). This remarkable stability is explained by similarities of features in the course of the main processes (erosion, karst, etc.) in different natural conditions and has been noticed previously in a qualitative form as the phenomenon of isomorphism of landscape patterns [Nikolaev, 1975]. Due to this property specifically, mathematical models of landscape patterns can be created without reference to a specific composition of sediments, precipitation, etc., for the territory of a given genetic type; specific conditions only affect the values of parameters in the model.

Mathematical models of complex morphological structures can be obtained theoretically on the basis of canonical models.

ANALYSIS OF RESULTS

The usage of mathematical models of landscape patterns provides answers to the aforementioned key issues of landscape metrics application.

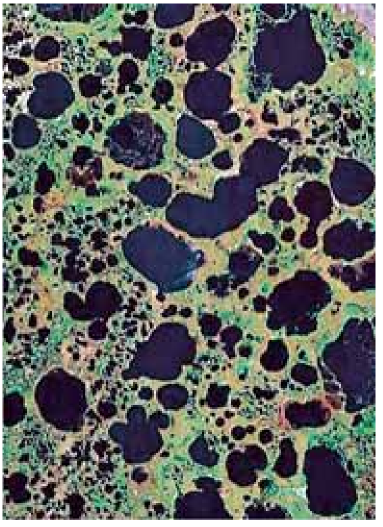

Fig. 1. A typical representation of the landscape pattern of thermokarst-lake plains on satellite imagery (West Siberia)

Values calculated from different metrics depend on their properties. However, little is known about whether parameters of landscape metrics are subjected to any laws and whether it is possible to forecast these parameters. Using mathematical models of landscape patterns allows one to predict what laws will govern the value of one or another landscape metric. We will demonstrate this by using the example of such a widespread metric as the area of the contour of a lake on a thermokarst-lake plain.

Let us consider the area of a thermokarst-lake plain uniform in soil and geomorphological conditions. The test area has a low-hilly sub-horizontal surface with the predominance of tundra vegetation (cotton-grass tundra, sedge-cotton-grass tundra, etc.) and with interspersed thermokarst lakes (Fig. 1). Lakes are isometric, frequently round in shape, and are randomly scattered over the plain.

The model can be based on the following assumptions:

1. The process of formation of the primary depressions is probabilistic and occurs independently in non-intersecting areas;

2. Thermokarst depressions generation occurs simultaneously; the likelihood of the formation of one depression in the test area depends only on its size (Δs) and it is much greater than the likelihood of the formation of multiple depressions, that is,

$$p_1 = \mu \Delta s + o(\Delta s) \qquad (1)$$

where μ is the average number of depressions per unit area;

3. The growth of the radii of lakes due to thermoabrasive impact occurs independently of each other, it is directly proportional to the amount of heat in the lake, and it is inversely proportional to the lateral surface area of the lake basin;

4. The depth of the lake is proportional to the radius.

The first assumptions seem natural, as derived from the homogeneity of the study area, and reflect the relative rarity of thermokarst depressions. The third assumption comes from the fact that the thermal effect is proportional to the heat flow through unit surface area. Finally, the fourth assumption reflects the fact that, along with increasing diameter of the lake, there is vertical thawing, though slow (this notion can substituted with the assumption of a constant depth).

The foundation of the model compiled allows one, through rigorous mathematical analysis of the assumptions, to arrive at the laws for such a widespread metric, as the area of the contour of a thermokarst lake on a thermokarst plain. It is possible to demonstrate that lognormal distribution of a thermokarst lake's radius follows strictly from the model assumptions [Victorov, 2006]. Since the logarithm of the lake area and the logarithm of its radius are in linear relation, it follows that the area of the lake will also be subjected to the lognormal distribution, i.e., for the density distribution of the lakes areas at any time (*t*) over the course of development of the site it is true

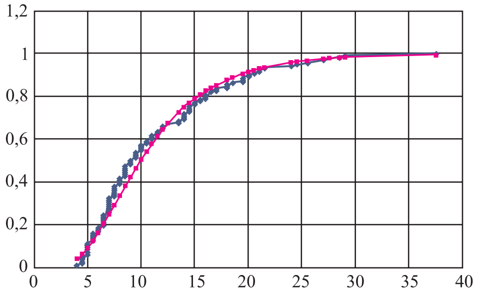

Fig. 2. An example of the comparison of the theoretical logonormal (magenta) and of the empirical (dark blue) distribution of the area of the thermokarst lakes (the experimental site)

$$f_s(x,t) = \frac{1}{\sqrt{2\pi}\sigma x\sqrt{t}} e^{-\frac{(\ln x - at)^2}{2\sigma^2 t}} \qquad (3)$$

where *a*, σ are the model parameters.

The conclusion has been empirically validated in real measurements based on remote sensing surveys for the sites in West Siberia, Alaska, and other areas [Victorov, 1995, 2006; Kapralova 2008 (Fig. 2).

Thus, although each lake area has its own value, their combination is subjected to a certain stochastic pattern; this pattern was obtained by mathematical analysis of the model. In general, we can conclude that the use of the mathematical landscape morphology approach to predict landscape behavior allowed forecasting values of landscape metrics for homogeneous physiographic conditions for the areas of thermokarst-lake plains. The type of distribution is lognormal and remains constant; the values of the distribution parameters vary depending on the specific physical and geographical conditions of each site.

Another key issue of development of the theory of landscape metrics is the relative informational content of different landscape metrics and of their combinations in problem solution. Typically, a researcher does not entertain the question and uses more or less suitable metrics contained in the well-known software tools and references [McGarigal, et al., 2002; Leitao, et al., 2006; etc.]. However, the analysis shows that, if some of the metrics are interrelated, sharing them is not rational, because it does not add information – a metric automatically confirms the differences identified by the other metrics. The interconnectedness of the metrics most often is not visible in advance and its detection is one of the main problems of using landscape metrics.

Approaches of mathematical landscape morphology can reveal hidden, at first glance, relationships of landscape metrics and, thus, evaluate their joint informational content. We will demonstrate this by the assessment of the joint informational content of three landscape metrics:

- the average area of a contour,
- the density of contours, and
- the share of the area under one type of contours.

Let us evaluate interrelationships of these metrics for a plain territory with the dominance of karst and subsidence-suffusion processes. Such territories develop in homogenous geological and geomorphological conditions and usually represent homogeneous landscape background with randomly scattered subsidings and rounded suffusion (or karst) depressions (Fig. 3).

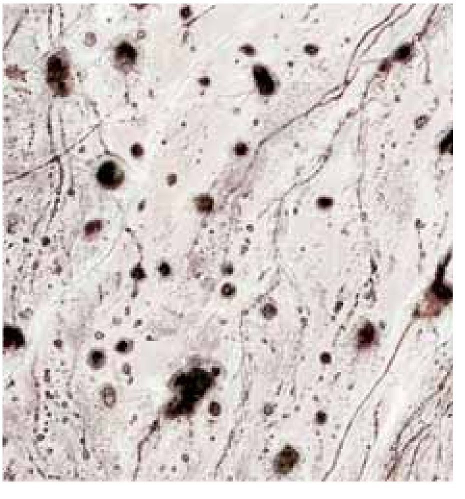

Fig. 3. A typical representation of a landscape pattern of the plains with subsidence-suffusion processes on satellite imagery (the foothill plain of Kopet-Dag)

The task of assessment of metrics relationships was solved not only for the genetic types of the territories, but also for a wide class of dangerous geological processes, with the centers of circular shapes, on the basis of mathematical models of landscape patterns. The assessment was based on the fact that processes prevalence, expressed by the average share of land area occupied by the centers of subsidence-suffusion processes, is equal to the probability of a point, randomly selected on a site of being within the limits of the center of the process. This, in turn, is a problem of the probability of subsidence-suffusion processes impact on small-size structures. According to the obtained solution for this problem [Victorov 2007b; Victorov, 2006], the following relation describes the impact:

$$P_d = 1 - e^{-\mu \bar{s}} \quad (4)$$

where μ is the mean density of the depressions locations; $\bar{s}$ is the average area of the depressions. The outcome has been subjected to the primary empirical test (Table).

Thus, the three metrics analyzed are in a hidden relationship, described by the expression provided above. Consequently, the use of the third metric (processes prevalence) does not add additional information for the mean density of the depressions locations and their average area. We emphasize that the evaluation of the informational content of the metrics has been conducted by the theoretical means; the experimental data have only confirmed the findings. The forecast of the relationships has been done using the models of landscape patterns.

One of the key questions in the theory of landscape metrics is the following: the extent to which landscape metrics reflect the dynamics of the landscape structure of the territory.

Let us examine this issue using the example of the plains dominated by thermokarst processes. Referring to the analysis presented above, it is easy to see that, for the thermokarst-lake plains, the average area of thermokarst lakes increases, reflecting the general dynamics of the landscape due to the degradation of permafrost on the edges of thermokarst lakes. However, let us consider the development of erosion-thermokarst plains in a situation where continued generation of new centers of thermokarst occurs.

The comparison between theoretical dependence of m1, m2, and m3 metrics and the empirical data

Locations of the test sites	Metric 1 (average density of depressions) km^{-2}	Metric 2 (average area of depressions) km^{2}	Metric 3 (processes prevalence)	
			Empirical values	Theoretical values
Turgai tableland (southern part)	0.111	0.820	0.106	0.087
Caspian lowland	1388.889	0.0002	0.209	0.188
Baraba steppe	0.899	0.307	0.198	0.241
Caspian lowland	11.364	0.008	0.070	0.090
Foothill plain of Kopet-Dag	81.439	0.001	0.053	0.073
Russian plain (Belarus)	148.448	0.002	0.250	0.224
West Siberia (South)	0.272	0.434	0.093	0.111
Turgai tableland (northern part)	0.364	0.354	0.053	0.129

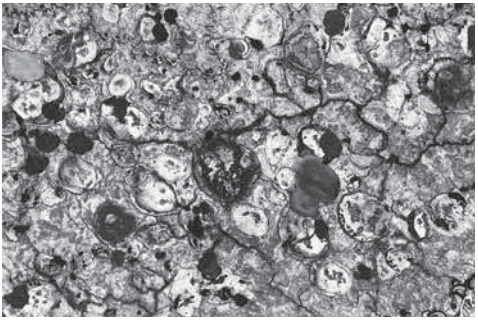

Fig. 4. A typical representation of the landscape pattern of erosion and thermokarst plains on satellite imagery

The test area has a low-hilly sub-horizontal surface with the predominance of tundra vegetation (cotton-grass tundra, sedge-cotton-grass tundra, etc.), which is interspersed with lakes and hasyreis and with infrequent erosion network. Lakes are isometric, frequently round in shape, and are randomly scattered over the plain. Hasyreis are flat depressions, also of isometric form, occupied with the meadow or marsh vegetation and, similar to the lakes, located on a plain in a random pattern (Fig. 4).

The basic assumptions of the model of the morphological structure of erosion and thermokarst plains satisfy the model of the thermokarst-lake plains presented above in the first positions, but are supplemented by two further assumptions that describe the interaction of thermokarst and erosion processes:

4. In the process of growth, a lake can transition to a hasyrei if it is drained by the erosion network; the probability of this even is independent of the other lakes; with it, the growth of the lake is terminated;

5. The location of the sources of erosion forms on a randomly selected site is a random event and its probability is proportional to the size of this site.

Also, the first assumption is modified, given the situation of a constant generation of new thermokarst lakes.

Thermokarst depressions generation is a random process; the likelihood of the formation of one depression on the test sites is independent and depends only on the area of the site (Δs) and the considered time interval (Δt); it is much greater than the likelihood of the formation of multiple depressions; that is,

$$p_1 = \lambda \Delta s \Delta t + o(\Delta s \Delta t) \qquad (5)$$

where λ is the average number of depressions that occur per unit area per unit time.

The complexity of analyzing the dynamics of this area is associated with the fact that there are two opposing trends on the site: the growth and the formation of new lakes on the one hand, and disappearance of lakes due to drainage through erosion processes and their transition to hasyreis, on the other hand. What is the dynamics of the territory after a considerable time?

Mathematical analysis of the model allows us to demonstrate [Victorov 2005b], that after a considerable time in a wide range of conditions on erosion-thermokarst plains, the dynamic equilibrium in the processes of generation of thermokarst lakes and their transformation to hasyreis is established. This dynamic equilibrium is characterized by the following dependencies in the morphological structure of erosion-thermokarst plains:

the density of the radii distribution of thermokarst lakes

$$f(x, \infty) - \frac{2}{xEi(-\pi\gamma)} e^{-\pi\gamma x^2}, \; x > 1, \qquad (6)$$

the average density of the locations of lakes

$$\eta(\infty) = -\frac{1}{2a} Ei(-\pi\gamma) \qquad (7)$$

the average area of a lake

$$\bar{s}(\infty) = -\frac{1}{\gamma Ei(-\pi\gamma)} e^{-\pi\gamma} \qquad (8)$$

the level of the processes prevalence, taking into account the incidence of thermokarst depressions generation, the growth of lakes, and their transformation into hasyreis

$$P_l(\infty) = 1 - \exp\left(-\frac{\lambda}{2a\gamma} e^{-\pi\gamma}\right) \quad (9)$$

the distribution of hasyreis radii

$$F_h(x, \infty) = 1 - e^{-\pi\gamma x^2} \quad (10)$$

where γ is the average density of the locations of the sources of erosion forms; *a*, σ are the model parameters; *Ei*(*x*) is the integral exponential function.

The findings obtained have also been subjected to the empirical test, which is shown in Fig. 5.

Thus, the analysis shows that such landscape metrics as the average area, density of locations, and share of the area of thermokarst lakeson erosion-thermokarst plains do not reflect the dynamics of the area. The reason is the state of the dynamic equilibrium with local changes (possibly intense) when the overall parameters remain constant and, thus, are not suitable for trend analysis.

The problem of capturing the dynamics of landscape metrics has another very interesting aspect. Above, we have discussed the question of controlling the dynamics of the territory by recalculating the values of the metrics over time. One may ask whether the values of landscape metrics *obtained at a single point of time* can carry information about the characteristics of the dynamics of the territory (the rate of development, the relationship of the rates, the probability of change, the duration of stages and their relation to each other, etc.). Such a formulation is of great practical importance, since it can dramatically reduce time-consuming stationary observations in predictions.

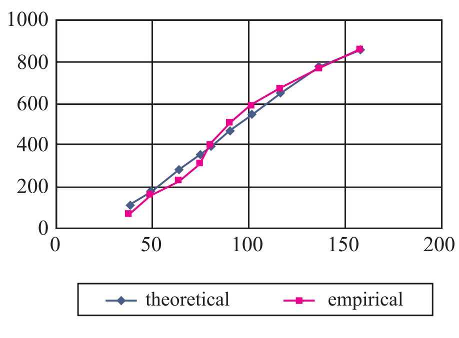

Fig. 5. The correspondence between the theoretical and empirical size distribution of the hasyreis (a part of the Yamburgskoye Gas condensate field)

Let us examine this question using an example of the landscape of alluvial plains. The principal elements of alluvial plains are oxbow (ancient oxbow) depressions and former riverbed elevations. The depressions have an arcuate shape, inherited from the former meanders, and are occupied by lakes, swamps, salt marshes, wetland forest vegetation, and tugai vegetation. The elevations, also of an arcuate shape, are occupied by more xeromorphic systems in accordance with the zonal, climatic, geological, and geomorphological conditions. The elevations and the depressions, adjoining each other, form patches coherent in shape and orientation. The patches of different generations adjoin each other, often "eating" parts of each other and, thus, forming the landscape pattern of the alluvial plains (Fig. 6).

A number of assumptions formed the basis of the mathematical landscape pattern models for the alluvial plains [Victorov, 1998;

Fig. 6. A typical representation of the alluvial plain on satellite imagery

2006], of which the most important for the solution of this task are:

The probability of the straightening of the bend over a certain time-interval depends on the duration of this interval and does not depend on the behavior of other bends;

$$p_d = \lambda \Delta t + o(\Delta t) \qquad (11)$$

where λ is the parameter; the probability of more than one straightening over a short time-interval is much smaller than the probability of a single one.

The formation of ridges occurs isochronously with the period φ.

The correctness of the model may be verified by validating the conclusion on the distribution of patch arrows[1]. The analysis of the model implies that the distribution of the cycle of the development of the bend and, correspondingly, the size of the patch in the direction perpendicular to the chord (i.e., the arrow) must meet the exponential distribution. This conclusion considers the fact that the straightening of the bend occurs repeatedly and that is why each younger patch "erases" the corresponding part of the preceding patch or the entire patch (Viktorov, 2007a). Several consecutive patches can be erased completely.

This conclusion was validated by processing remote sensing data for the alluvial sites of the valleys of the rivers Vakh and Taz. Satellite images of 5-m and 15-m resolution were georeferenced using GIS MapInfo. The arrows of the fragments of the patches were drawn reflected their size. The arrows in the young developing patches were drawn as a perpendicular between the patch base (a straight line) and the parallel line tangent to the top of the patch. The arrows in the fragments of the old patches were drawn as a perpendicular between the line tangent to the top of the arc of the fragment base and the parallel line tangent to the top of the arc that delimited the patch fragment on the outside. In some cases, there were difficulties associated with the erasure of the side parts of the fragments due to the shift of the channel, but in general, despite these uncertainties, in most cases, it was possible to draw the arrows. Adjacent fragments of the patches were isolated on the basis of angular unconformities.

The curves of the empirical distributions were constructed from the measurements results:

- the size of the young growing patches;
- the size of the entire set of the patches.

Further, the average values for the samples was determined and the empirical distributions were compared with the theoretical exponential distribution with the shift, according to the results obtained. The use of the distributions with the shift was connected with the fact that the analysis of the images showed fragments of the patches consisting of at least two ridges and one inter-ridge depression; there were no fragments consisting of one ridge only. The comparison (Fig. 7) shows that the results of the model are supported by the empirical data by both the relationship of distribution curves and the Pearson criterion at a significance level of 0.95. However, more reliable results are obtained when applying the criterion for the sample-size of more than 50.

The use of the obtained conclusion on the distribution of the duration of the cycle of development of the bend allows obtaining the distribution of the number of ridges in the patch. Considering steady generation of the ridges in time, it is possible to see that it is described by the expression

$$P_v(m) = e^{-m\frac{\varphi}{\mu}}\left(1 - e^{-\frac{\varphi}{\mu}}\right) \qquad (12)$$

where φ is the average period of the formation of a ridge; μ is the average duration of the formation of the bend.

[1] By analogy with the rise of an arc, which is the line perpendicular to the chord that goes from the center to the apex of the arc.

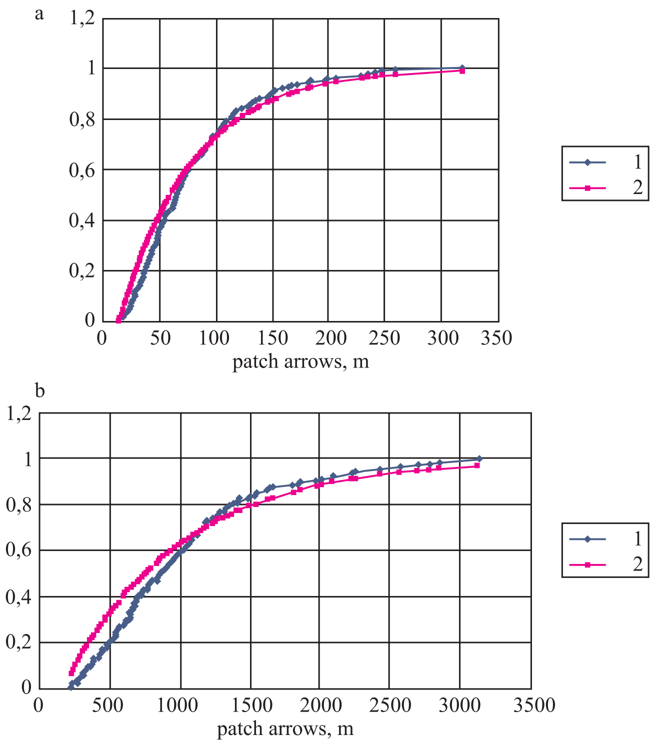

Fig. 7. The comparison of the experimental curve of the distribution of the sizes of the arrows of the preserved fragment of the formed patch (*1*) and of the theoretical curve of the exponential distribution with a shift (*2*) for the areas of the alluvial plains of Western Siberia:

a – the valley of the river Vakh; b – the valley of the river Taz

It follows that the average number of the ridges in the patch may be given by the expression

$$\bar{v} = \frac{e^{-\frac{\varphi}{\mu}}}{1-e^{-\frac{\varphi}{\mu}}}. \quad (13)$$

The latter expression makes it possible to obtain the value for the dynamic parameter, which is the ratio between the period of the straightening of the bend and the period of the formation of the ridge

$$\frac{\varphi}{\mu} = \ln\left(1+\frac{1}{v}\right). \quad (14)$$

Thus, the dynamic parameter of the alluvial plains that describes the relation between the period of the bend straightening and the period of ridge formation may be defined by using such landscape metric as the average number of ridges in the patch. We emphasize that the metrics values are determined from a single period of observations.

CONCLUSIONS

Thus, this study suggests the following conclusions.

The values of landscape metrics are subjected to stochastic patterns specific to each landscape.

The joint informational content of various combinations of landscape metrics varies and can be predicted.

Landscape metrics in different landscapes reflect their dynamics to varying degrees and this can be forecasted; the values of some landscape metrics obtained for one period, however, reflect temporal parameters of the landscape dynamics of the area.

The key issues in the use of landscape metrics can be addressed using theoretical approaches based on mathematical landscape morphology. ■

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