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The scaling and the modern dynamics of ecological complexity: aerospace monitoring

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Abstract. State-of-art of biogeography of terrestrial ecosystems under antropeic impact is based on the study of large-scale spatial heterogeneity and long-term dynamics of ecological complexity. We used the Eurasian network of long-term ecological and remote sensing researches on test areas over the former USSR. Spatial scaling of ecological complexity in quantitative terms has been completed for discrete identification of hierarchical scale levels of terrestrial ecosystems. Study of hierarchical temporal scaling and long-term dynamic systems includes remote sensing monitoring, mathematical modelling and ecological forecasting.

Key words. Landscape ecology, Spatial and dynamic biogeography, hierarchical classification, long-term dynamic modelling and forecasting.

INTRODUCTION

Scaling and modelling of the long-term dynamics of ecological complexes were performed within the framework of the Russian Committee of MAB/UNESCO by WG on Aerospace Methods in Ecology during the last decade. The programme of these studies was founded by the First International Congress on Biosphere Reserves, held in Minsk at 1983 (Vinogradov, 1984) and by the UNEP/UNESCO Symposium on the State-of-the Art of Remote Sensing Technologies to Biosphere Studies, held in Leningrad in 1988 (Dyer & Vinogradov, 1990).

For this paper we use the network of long-term ecological and remote sensing researches on test areas over the former USSR. Each test area is a representative complex ecosystem with a size of no less than 100 km^2 (some as large as 1000 km^2), monitored long-term for no less than 20–30 years (beginning in the 1950s) and covered by repetitive aerial and space surveys for 5–10 years. They provide us with multistep bottom-up data integration from patches to regions. Three main objectives of long-term ecological researches are pursued on our test areas:

1. Study of *hierarchical spatial scaling systems* provides us with quantitative patch models and multistep data generalization from elementary biogeocenotic units of 10 m to regional ecological units of 100 km.
2. Study of *hierarchical temporal scaling and long-term dynamic systems* includes long-term aerospace monitoring, probabilistic mathematical modelling of the long-term dynamics of complex ecosystems, ecological prediction and optimization as derived from models.

TABLE 1. The network of the aerospace ecological test areas for global change of terrestrial ecosystem studies.

Name	N. latitude	E. longitude
Pechenga-Nickel region with air pollution of the Kola northern forests	69 26	30 40
Estonian mires under drying, management and conservation	58 40	26 24
Kostroma biostation environs with deforestation of southern taiga forests	58 15	44 20
Livonian plain with agriculture management of forest–swamp–field ecosystem	56 36	25 14
Karabash region with air pollution of the Middle Ural mixed forests	55 27	60 12
Berezinsky Biosphere Reserve with deforestation and conservation of mixed forests	54 42	28 24
Black Lands with severe overgrazing and desertification of Kalmykian sand subdeserts	45 30	46 30
Amudarya Delta with severe drying and desertification	43 26	58 56
Badhyz biosphere reserve with zoogenic desert successions	35 46	61 58

3. Study of *climatic effects of the long-term dynamics of terrestrial ecosystems* attains fulfilment of previous objectives and describes the influence of patch dynamics of terrestrial ecosystems on radiation, water and matter balance of the earth–atmosphere system.

The network of test areas covers different landscapes with various dynamic processes within the former USSR. These long-term ecological and remote sensing researches on our test areas (Table 1) correspond to the work the International Geosphere–Biosphere Programme (IGBP) 'Global Change' (1993, 1994) and to the GCTE Core Project (Walker, 1994).

HIERARCHICAL SPATIAL SCALING SYSTEMS

Work Plan IGBP 1994–98 declares in GAIM that 'the spatial and temporal scaling is recognized to be an important issue on which progress is needed and could be achieved in parallel with GCTE' (p. 100). In our paper *scaling* is the revealing of the discrete hierarchy of spatial structures of the biosphere. Scaling of ecological complexity in quantitative terms has been completed for discrete identification of hierarchical scale levels of terrestrial ecosystems (Vinogradov, 1976).

Approach to spatial scaling systems

For scaling ecological units the relation of spatial frequency distribution F to ecosystem size L was measured by scanning multiscale aerial and space photographs. This relation $F(L)$ has been described, in analytical form, as a power function with negative power index on which is overlaid a trigonometric function with regular sinusoid waves. The implicit form of this relation is the following:

$$Y = \lg a - bX + c \sin X \text{ with } Y = \lg F,\ X = \lg L, \qquad (1)$$

where $\lg a - bX$ is an hyperbola in coordinates of F and L, $c \sin X$ is sinusoid, the amplitude of which is decreased and the wavelength is increased in geometrical progression, with growth of L having the base of period near π. For scaling we used various techniques of morphostructural studies: mathematical modelling, comparative multiscale cartography, photometric scanning, morphometric image analysis, optical conversion, statistical generalization, information value comparison, etc. It has the scale step of almost 3.1–3.3-fold of difference in linear size of ecosystem dimensions between successive scale levels (Vinogradov, 1989).

This discrete hierarchy has the advantage of equal distances between levels, with no failures between them. It has been adapted for French (Forman & Godron, 1986) and Dutch (Pedroli, 1983) research and later analogous proportional hierarchies were also formed in other countries. Analogous hierarchical systems have been shown in other sciences: in geophysics it has been found that interrelation between successive organization levels of block structure from stratus to the Earth's crust varies from 2.5 to 5.8 (average 3.3).

TABLE 2. Scaling of spatial ecological units for global change of terrestrial ecosystem studies.

Scale level	Universal unit name	Common unit name
1:300,000,000	Exachore	Biosphere
1:100,000,000	Petachore	Dominion, zone
1:30,000,000	Terachore	Subzone, biome
1:10,000,000	Gigachore	Ecoregion
1:3,000,000	Megachore	Province
1:1,000,000	Macrochore	Landscape
1:300,000	Mesochore	Land system
1:100,000	Microchore	Combined land unit
1:30,000	Nannochore	Simple land unit, land type
1:10,000	Monochore	Biogeocenosis, land site
1:3,000	Piccochore	Parcel, Keller's complex
1:1,000	Femtochore	Synusium, mosaic

Universal spatial scaling system

Thus, we recognize twelve discrete scale levels during integration from the synusial structure of populations on a scale of 1:1000 with resolution of 0.03 m, to elementary biogeocenosis on a scale of 1:10,000 with resolution of 0.3 m, to the zonal structure of the biosphere on a scale of 1:100,000,000 with resolution of 30 km. These scaling levels were named using the prefixes *femto-*, *picco-*, *mono-*, *nanno-*, *micro-*, *meso-*, *macro-*, *mega-*, *giga-*, *tera-*, *peta-* and *exa* added to the root *chore*. This quantitative step-by-step scaling allows correct regional and global data to be collected using ground observations over test areas and multiscale aerospace surveys between them.

Reviewing different classifications of spatial ecological units and its scale hierarchies we note that they correspond badly to one another. Because of this, we have tried to form a universal scale hierarchy of spatial ecological units that has integrated different classifications (Table 2).

HIERARCHICAL TEMPORAL SCALING AND DYNAMIC SYSTEMS

In GCTE 'much of change of the Earth's land cover is driven by processes which occur at the landscape scale (1:10 km) for incorporating these processes into regional and global ecosystem dynamics models' (p. 44). The GCTE landscape programme will work in close collaboration with the LUCC Core Project, which is based on a series of regional case studies (our test areas).

Mathematical modelling of the modern dynamics of ecological complexes needs accurate comparison of multiyear aerospace imageries and ground observations (Vinogradov, 1988). This approach permits the description of trends of simple ecosystems by the ranges of algebraic equations. The most advanced and adequate approach to modelling of the modern dynamics of complex ecosystems is based on the approximation by Markov chains: using comparison of two data surveys we compile Markov chains of the first order; tree surveys, the second order, etc. The greater number of repeated surveys the more adequate the model of non-linear dynamic processes. This technology provides normative prediction of ecosystem changes for 10–20 years hence. Moreover, operations under transition matrices permit the dating of the time of destablization of ecosystems in the past, or to forecast the time of stabilization of ecosystems in the future.

Forecasting of simple ecosystem dynamics

Sequential ground observations, aerial photographs (1954–84) and space surveys (1975–84) over the Black Lands test area during the course of 30 years were used in a mathematical expression of the trend of area dynamics of deflation scarps and mobile sands. The growth of this desertification area, as indicated by the enlargement of the area of deflation scarps and mobile sands, can be described by an exponent function:

$$Y = a\ \exp(\alpha(X_1 - X_o)) \qquad (2)$$

where Y is the relative area of deflation scarps and mobile sands, as was seen in aerial photographs, for the current year X_1, a is the area of deflation scarps and mobile sands for the year before onset of the process, when the ecosystems were in a stable state X_o, (assumed to be 1954), α is the power showing the accelerated increase in the area of deflation scarps and mobile sands.

Operations with mathematical models of the long-term dynamics of simple ecosystems allows prediction of the near-future ecological state over different test areas. Therefore, knowledge of the current tendency of the dynamics of deflation scarp and drift sand area over the Black Lands test area (see eqn 2) makes ecological forecasting possible. It is assumed that having determined the current tendency from 1954 to 1984 it could be extrapolated to the future by at least one-third of the investigated time interval, i.e. in our experiment 10 years forward to 1994. According to eqn 2 and considering a representative time interval, we find that bare and drift sands devoid of soil and vegetation would occupy 56% of our test area by 1986, 84% by 1990, and 100% by 1992.

Forecasting of the complex ecosystem dynamics

Mathematical modelling of complex ecosystem dynamics is more complicated. However, forecasting on the basis of such complex analysis is more correct (Vinogradov, 1989, 1992).

Previously we used simple Markovian chains for ecological forecasting. These simple Markovian chains were compiled from comparison of two sets of aerospace survey data sets. According to this procedure the simple transition matrix for all ecosystem classes during the training time interval $M_{1\text{–}2}$ was multiplied by the transposed vector of final state V_2 of each ecosystem class within the study area. As a result, we received a prognosed vector for forecasted state V_3 on one time interval forward:

$$V_3 = M_{1\text{–}2} \times V_2. \qquad (3)$$

Over the Lower Amudarya Delta test area the transition matrix $M_{1980\text{–}85}$ served as a training sequence of the ecosystem area dynamics for ecological forecasting for 5 years ahead. Subsequently, $M_{1980\text{–}85}$ was multiplied by the vector of final state V_{1985} and we received the prognosed vector on 1990, i.e. V_{1990}. After this, received $M_{1985\text{–}90}$ could be multiplied by V_{1990} for receiving of prognosed vector V_{1995} (i.e. forecast for 1995), then similarly for 2000, etc.

At the present time, taking into account the non-linearity of dynamic trends, we prefer to use inhomogeneous transition matrices, which need more than two survey times for the same test area. For compilation of these inhomogeneous transition matrices we used photo-interpretation maps of three survey times (1975, 1980, 1985) which had been received from spacecraft Salyut 4, Salyut 6 and Salyut 7. A normative forecast of the ecosystem dynamics to 2010 reveals area changes of ten ecosystem classes (Vinogradov, Frolov & Popov, 1990), in which predicted trends of area changes of ecosystem classes for 1985–2010, based on training sequence of area changes for of 1975, 1990 and 1985 space surveys, were computed for ten ecosystem classes (Table 3).

The most rapid growth is predicted for desert ecosystems by two-and-a-half times and for saline systems by three times in comparison with 1985. These two arid ecosystems could occupy nearly 70% of the whole area of the Lower Amudarya delta by 2010. Conversely, the area of dry meadow ecosystem class would be decreased by nine times, wet meadows by thirty times, and the whole area of mesomorphic ecosystem classes will decrease to 5% of the delta. Some ecosystem classes would disappear in the near future (for example, wet meadows by 2000, true meadows/tugai forests and shrubs by 2005). However, two ecosystem classes will not change their area significantly: irrigated fields will be supported on a level of almost 13–14% by man's efforts. Subsequently, the predicted trend of area of intermediate saline desert ecosystem class would have a fluctuating form on the subclimax level.

TABLE 3. Predicted dynamic trends of severe desertification of ecosystems over the Lower Amudarya Delta test area using Markov chain approximation.

Ecosystem classes	1980	1985	1990	2000	2010
	Measured		Control	Predicted	
1	2.65	4.84	7.29	9.38	10.00
2	6.84	5.69	4.79	3.75	1.25
3	9.37	5.77	3.54	0.00	0.00
4	4.64	4.18	3.54	1.67	0.63
5	30.24	25.08	18.32	5.83	1.88
6	3.46	7.51	12.84	21.25	29.38
7	10.16	7.51	4.79	0.83	0.00
8	9.80	12.48	15.58	14.74	11.16
9	9.49	13.25	20.48	32.92	37.29
10	13.25	13.69	14.53	14.11	13.68

1: saline swamps; 2: swamps/water bodies; 3: wet meadows; 4: meadows/tugais; 5: saline meadows; 6: true salines; 7: dry meadows; 8: saline deserts; 9: true deserts; 10: irrigation fields.

Control of forecasts

Experimental control of forecasts is under way: the procedure of epignosis. According to this procedure, the previous time interval was used as a training sequence of ecosystem dynamics for forecasting the ecosystem state of recent time, which could be tested during field control studies. In our Amudarya Delta test area the transition matrix $M_{1975–80}$ was used as a training sequence for prediction of area changes to 1985. Then, predicted areas of all ecosystem classes V_{1985} were tested during field travels in 1985. The comparison of predicted and tested areas for 1985 reveals a mean error of forecast for 5 predicted years, equal to 10.65% of the whole changed area. For longer prediction time errors will be larger. We estimated the mean error for 10 predicted years near 16%, for 15 near 25%, etc.

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