Experimental
Geographical Ecology

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Problems and Methods

By

Erland G. Kolomyts

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By Erland G. Kolomyts
Institute for Fundamental Problems of Biology, Pushchino Scientific
Center of the Russian Academy of Sciences

Edited by Gennady S. Rozenberg

This book first published 2022

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-8664-2
ISBN (13): 978-1-5275-8664-2

This book sets out a paradigm of experimental geographical ecology and its core – landscape ecology – providing a number of empirical statistical models and ecological geographical concepts developed on the basis of these. It highlights the mechanisms of the formation of regional- and local-level landscape-ecological systems, their natural and anthropogenic dynamics, and their evolutionary trends. It presents numerical methods of making landscape-ecological forecasts and assessing forest sustainability, and provides quantitative estimates of local and regional biotic regulation of the carbon cycle according to the scenarios of modern temperature growth and mitigation of warming, set out by the Paris (2015) Agreement on Climate Change. The book will appeal to specialists in the fields of geographical ecology, landscape-ecological modeling, and environmental forecasting.

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FOREWORD

The book describes the author's paradigm of experimental geographic ecology and its core – landscape ecology. The entire array of scientific and methodological developments is systematized in such a way as to reveal the content of experimental geoecology using multidimensional system analysis, enriched with empirical-statistical models of basic and predicted states of the geo(eco)systems as integral and dynamic formations. The author describes the empirical-statistical models created by the author over the past 40 years and the landscape-ecological concepts developed on their basis: geo-ecotonic, landscape-zonal poly-morphism, paleo-forecast (in the light of global climate changes), forecast-topological, and high-mountain geo-ecological. A special place is occupied by the experimental geo-ecological analysis of the Pacific mega-ecotone of Northern Eurasia as an evolutionary model of the continental biosphere.

These concepts reveal the mechanisms (including processes) of the formation of landscape-ecological systems at both regional and local levels, their natural and anthropogenic dynamics, as well as evolutionary trends. The landscape-ecological analysis was carried out on specific examples for the territory of Russia (the Volga River basin, the Central Caucasus, the Middle Urals, the Lower Amur Region, and the Southern Kuril Islands), using a mass of field factual material and using methods of empirical simulation of calculated predicted situations.

The forecast-ecological analysis itself is based on the method of numerical landscape-ecological forecasting for the first time developed by the author. The technique has been brought up to the prescription level. It organically combines, on the one hand, a fairly strict formalized approach to solving forecasting problems, and on the other, the availability of procedures for collecting, processing and analyzing empirical material for a wide range of researchers.

This voluminous book contains the important results of the landscape-ecological researches of the author over the past 40 years, as well as the developments in the methodological and informational terms of physical geography and landscape ecology. This makes the monograph interesting and very useful as a reference book for field research, statistical and cartographic processing of the obtained data, mathematical modeling, geoecological information interpretation of results and creation of theoretical schemes of geosystem analysis.

The book is intended for biogeographers and physical geographers specializing in the fields of theory and methods of landscape ecology, landscape-ecological modeling and forecasting, and geosystem monitoring, as well as the study of evolutionary biospheric processes. It should be noted that the Russian school of the landscape science, which is the ideological basis of the present work, is not very well known for many West European and American investigators. For this reason, the given monograph may be interesting theoretically and methodically both for landscape scientists and for multi-skilled ecologists.

Prof. G.S. Rozenberg,
Corresponding member of the Russian Academy of Sciences,
Chief Scientist of the Institute of Ecology of the Volga River Basin of the Russian Academy of Sciences

PREFACE

The convergence of complex physical geography and ecology is one of the main trends of the modern development of the sciences concerned with the natural environment. This trend opens new prospects in studying natural regimes by using experimental methods and environmental system structure analysis to optimize nature in respect of resources and ecology (Sochava 1974) and developing the methodology and ways of environmental protection and landscape planning (Ruzicka and Miklos 1982; Demek 2000; Antipov et al. 2002). As early as in 1952, when stating the principles of geobotanic studies, L.G. Ramensky wrote:

> "Ecology is the only language in our field, which can be a potential basis for reaching the really complex coverage of the subject in its diversity and unity" (1971 157).

The interpretation of ecology

> "… as the science concerned with the structure, and functions of nature" (Odum 1975 10)

has already been recognized, which is quite in agreement with the objectives of the theory of geosystems (Sochava 1970, 1978). The synthesis of these scientific trends resulted in the establishment of *landscape ecology* (D.L. Armand 1975; Forman and Gordon 1986; Forman 1997; Vinogradov 1998; Rozenberg et al. 1999; Wu and Hobbs 2002), one of its major problems being an investigation of the structure and function of local natural complexes (Preobrazhensky 1982). Though the modern landscape ecology goes far beyond the scope of topology and is considered the science concerned with the functional unity of spatial structures of abiotic, biotic, and anthropogenic components of any dimensions (Lezer 1997; Naveh 2000), we will keep to the original, classical definition of this science. Concerning the entire poly-scale system of natural complexes, from landscape facies (biogeocoenoses) to zonal-belt and large regional units of the continental biosphere, we will accept the more general concept of *geographical ecol*

> "The time of "patchwork ecology" swiftly passes, giving place to the complex (now referred to as "systematic") approach to the description of processes, and events" (Shitikov et al. 2008 215).

The systematic approach proposes the use of a very broad concept in the research process: organization, the orderliness of landscapes or ecosystems. This concept includes two interdependent parts: (1) internal orderliness, consistency of and interaction between parts (elements) of the whole; and (2) the set of behavioral (function), control, and self-regulation processes at each structural level. The geographical aspect of system organization consists in the search of mechanisms for connecting natural components diverse in their genesis, substrate properties, and rate of change, as well as lower-rank complexes, into a single integral formation (Preobrazhensky 1986; Moss 1999). The analysis of connections within a geo(eco)system and between systems is the essence of landscape-ecological research.

Many experts consider remote sensing as the main source of data for landscape analysis and propose "hierarchic patch dynamics (HPD)" as a theoretical structure for solving the problems of heterogeneity or homogeneity of scale, neighborhood, and similarity (Hay et al. 2001; Burnett and Blaschke 2003). The main attention is focused on the effects of interaction between spatial structure and ecological processes (Pickett and Cadenasso 1995), taking into account that the structure–process relationships are scale-dependent. It is a basis of the paradigm of hierarchic dynamics of spatial units (Wu and David 2002).

In recent decades, landscape ecology has transformed into a "global science" (Wu and Hobbs 2002), with two basic approaches: bioecological and geo-ecological (Moss 1999). Nevertheless, there is a quite reasonable opinion (Farina 1998) that landscape ecology cannot be a comprehensive environmental science.

The efficiency of the ecological approach to nature research is as follows: first, the entire closed contour of forwarding and backward connections in the object-environment system (not only the closest, direct, but also remote, indirect) is studied and, second, now it is possible to predict the state of necessary natural components under the anthropogenic impairment of particular elements of ecological connections. The latter circumstance should be especially emphasized because the necessity of wide introduction of the ecological concept into Earth sciences and the practice of monitoring (Izrael 1984) is determined by the increasing energy availability for mankind and the dramatic increase in the human technogenic impact on nature, which occurs before our eyes. Since the problem consists in the preservation of not only landscape bio-components but also other natural resources important for humans (clean atmosphere, natural waters, earth interior, etc.), one can speak about *landscape ecology* in general, including man as a biological and social individual, i.e., *geoecology*. Though the concept of geoecology was proposed by C. Troll in 1968, the content of this concept was explained by V.V. Dokuchaev and G.F. Morozov as early as 100 years ago (Isachenko 1971).

In geography, the principle of expediency and efficiency of ecological approach for studying terrestrial systems of any physical nature has been substantiated (Mints and Preobrazhensky 1973). This principle was later developed in the generalizing tutorial by A.G. Isachenko (2003), where he considered the principles and methods of ecological-geographical studies, including the analysis of the anthropogenic transformation of landscapes and their resistance to technogenic loads. The author has performed ecological-geographical classification (zoning) of Russia and reviewed the modern state of landscapes for large regions of the country.

At the same time, the geographic-genetic approach is widely implemented in the study of plant and animal communities. For example, the modern forest typology relies on regularities of the structure and evolution of natural landscapes as a necessary methodological basis for developing the general theory of forest formation process (Kolesnikov 1967; Rysin 1980).

The implementation of the ecological approach in many natural sciences is associated with the better understanding of the role of biological components of landscape in its stabilization and self-regulation, as well as with the drastic aggravation of the problem of nature protection in recent decades under the conditions of worldwide scientific and technological revolution and powerful social and cultural shifts in human society. The development of the geo-ecological concept manifests itself not only in filling the old term "landscape science" with the new ecological content but also in outlining the first steps in the development of a constructive-transformative trend in Earth sciences, in particular, geography and biology (Gerasimov 1985).

In the English-language (especially American) literature it is proposed to shift the center of gravity of research from spatial structures to natural processes giving rise to these structures. This postulate is claimed as a new stage of development of landscape ecology (Forman and Gordon 1986; Neill et al. 1988; Forman 1995; Farina 1998; Wu and Hobbs 2007; etc.). Such statements of foreign colleagues unfamiliar with the literature published in Russia can only cause bewilderment. It should be recalled that the foundation of this (genetic) trend in natural geography was laid by

V.V. Dokuchaev (1881), and it has been predominant since the very first stages of the development of Russian landscape science and landscape ecology (Vysotsky 1909, 1949; Ramensky 1971 (1930); A.D. Armand 1975; Solntsev 2001 (1949); etc.) and biogeocoenology (Sukachev 1960, 1972). These fundamental Russian works were drastically different from the works of the USA – West European chorological (Hettner's) trend, which is unreasonably considered the "period of classical landscape ecology" (Forman and Gordon 1986; McGarigal and Marks 1995; Khoroshev et al. 2006, 2016; Khoroshev 2013; etc.).

In particular, the problem of describing spatial structures through spatial processes was posed in a rather complete form by I.P. Gerasimov (1986) as early as in 1964 in its neo-Dokuchaev paradigm of soil science: "environment (soil formation factors) – soil processes (genesis) – soil properties", – when addressing the issues related to soil classification and soil mapping. The analogous "conditions – process – structure" functional triad later became a basis of the conceptual model of geographical ecotone as a hierarchic system of control (Kolomyts 1987). The theory of Grigoryev (1966) about the multi-aspect but essentially integral physical-geographical process forming the zonal-belt structure of geographical envelope is of fundamental significance. Global biosphere processes, which formed the main natural-territorial structures of the Earth at all stages of its geological development, were disclosed in the works by Budyko (1975, 1984). At the local and subregional levels, one should note the conceptual provisions of V.B. Sochava (1962, 1978) concerning the evolution and dynamics of geosystems, their factorial-dynamic series, and self-regulation regimes determined by the interaction between soil hydro-thermics and plants. Earlier, the effects of local hydro-edaphic regimes on plant communities under different geomorphological conditions were studied in detail by Vysotsky (1909, 1949) and Tanfilyev (1953). Armand (1975) distinguished a special physical-ecological trend in landscape science concerned with matter-and-energy landscape-forming processes. He also proposed the term of "landscape geophysics". Finally, we cannot but mention the phyto-edaphic aspect of G.F. Morozov's theory of forest types (1949), the geomorphological and climatic complexes of the types of forest communities by Kolesnikov (1956), as well as the concept of eco-genetic (demutational) changes and exogenous (phylocoeno-genetic) transformations of biogeocoenoses proposed by V.N. Sukachev (1975) and developed by Razumovsky (1981).

The author's long-term search in the field of geographical (landscape) ecology was based precisely on this rich experience of Russian natural science. The entire contents of this monograph are a certain logically ordered ensemble of basic and predictive empirical-statistical models and the concepts developed on their basis, which reveal the mechanisms of formation of both regional and local landscape-ecological systems, their natural and anthropogenic dynamics, as well as evolutionary tendencies (at the geological scale of biosphere evolution). Landscape-ecological analysis was performed with particular examples, with the involvement of quite an array of factual field data, in contrast to the much less informative remote sensing data used by foreign analysts (see above). The author strongly believes that it can be most informative for the experts in physical geography concerning the essence of problems under consideration and the proposed methods of their solution. This is precisely the specificity and scientific-methodological significance of *experimental geographical ecology.* Here, it would be appropriate to cite the known statement of Isaac Newton: "When studying sciences, examples are more useful than rules". The landscape-ecological analysis was carried out using concrete examples (the Volga River basin, the Central Caucasus, the Middle Urals, the Lower Amur Region, and the South Kuril Islands), using the mass of field evidence and empirical methods for simulating predicted situations.

The whole array of scientific and methodological developments presented in the monograph was systematized and generalized in such a way that to present experimental geographical ecology at the modern level of development of Earth sciences, with the involvement of systematic analysis enriched with the empirical-statistical models of basal and predicted states of geo(eco-)systems as integral and dynamic natural-territorial formations (in keeping with the spirit of the doctrines by G.N. Vysotsky, V.V. Dokuchaev, L.G. Ramendky, V.N. Sukachev, L.S. Berg, A.A. Grigoryev, V.N. Timofeev-Resovsky, and V.B. Sochava).

Our studies proceed from the above-mentioned most general concept of ecology. It suggests the wide integration of ecological and landscape-geographical methods of research, with the interpretation of natural environment concerning the theory of systems, which makes it possible to establish the mechanisms of ecological connections in particular geospace (Sochava 1970). Landscape organization is known to include the two interrelated but opposite processes: integration of different geo-components into holistic natural unities (landscapes) and differentiation of these unities into relatively detached territorial parts of different scales, i.e., subordination of their structural levels – local, regional, and planetary. Such dual organization of geographical space (integration–differentiation) is reflected in the two branches of geo(eco)system hierarchy: components and areal (Gettner 1930). Accordingly, there are two types of landscape organization models: mono-systemic and polysystemic (Preobrazhensky

1969). The entire complex of relationships between natural components and factors providing the existence of ecosystem diversity is a subject of geographical ecology.

We consider mainly *physical ecology* which, by the analogy with landscape physics (Armand 1967), analyzes the physical processes of interaction between biota and abiotic factors, which determine the structural and functional organization of natural ecosystems with a particular level of their primary productivity. Here, we should mention Gerasimov's ideas that

> "… the heat and moisture cycle in the natural environment is always and everywhere the principal mechanism that controls the intensity and character of all other forms of energy and matter exchange between the major components of geographical environment … Moreover, it should be considered that different spatial variations terrestrial surface related to global and local factors determine diverse geographical modifications in the pattern of this exchange to a greater extent than anything else" (1993 235).

Of course, biogeochemical cycles, as well as biotic interactions in ecosystems, are no less important; however, we do not consider the latter aspect of ecology.

The ecological safety of the most developed economical regions of our country is largely associated with the problem of forest conservation and reproduction – first of all, in the south of the boreal belt and in the north of the sub-boreal belt, i.e., under critical conditions of zonal forest-to-steppe transitions. This problem becomes especially pressing in light of increasing anthropogenic impacts on nature, which now reach a global scale. Such phenomena of the modern stage of interaction between nature and society include the already beginning anthropogenic global climate change (global warming), with its highly diverse and sometimes hardly predictable ecological consequences (Albritton et al. 2001). From 1950 to 1996, atmospheric concentrations of carbon dioxide increased from 1.6 to 5.9 million tons at the expense of world carbon emission from fossil fuel burning. World sulfur and nitrogen emissions from fossil fuel burning increased within this period from 30 to 70 million tons. As a result, the average global temperature rose from $14.8–14.9^0$ to $15.2–15.4^0$ (Komdratyev and Calindo 2001).

Among the most dangerous ecological consequences of global warming and total climate aridization of the natural environment may be the irreversible impairment of forest growth conditions on the vast territories of southern marginal forests of the temperate belt. Further progressive climatic aridization may lead to catastrophic consequences for terrestrial biota in general. The recent studies of volcanic rocks from the Tunguska River banks performed at Syracuse University (United States) have shown that "the Great Permian Extinction", when up to 95% of living creatures disappeared from the face of the Earth, was determined by enormous volcanic outbursts of greenhouse gases to the atmosphere. It is also supposed that already 2020 will probably be "the ecological point of no return", if the global flow of technogenic emissions of greenhouse gases it not reduced following the Kyoto Protocol and Paris Agreement.

The Project of Annual Report of the Ministry of Natural Resources and Forestry "On Environmental Protection" of 2018 reported a substantial increase in greenhouse gas emissions, caused mainly by economic growth and human population growth. It leads to unprecedented (at least, in the past 800,000 years) levels of atmospheric concentration of carbon dioxide, methane, and nitric oxide. As a result, the mean annual air temperature increased all over the globe by 0.18^0 C on average every 10 years in the period from 1976 to 2017. In the territory of Russia, this increase was much higher: 0.45^0C/10 years. It has been established that more than 95% of global warming is determined by anthropogenic effects on the climate.

The high priority ecological-geographic objectives for solving the problem of global warming are as follows: (1) establishment of the mechanisms of the response of forest communities of the temperate belt, which are located near the southern boundaries of the area of their distribution, to the unfavorable effects of total environmental aridization caused by global warming and (2) development of model ecological scenarios of structural and functional organization, stability and carbon balance of forest ecosystems according to the global models of climate changes for the next 100–200 years. A considerable part of this monograph is devoted to the solution of these fundamental problems.

The known methods of bioecological and geosystem monitoring, which are most often based on the comparative analysis of aerospace data, do not operate with the parameters of the biological cycle in geo- and ecosystems; therefore, they cannot reveal any functional relationships between the biota and the environment or predict the changes in these relationships. Accordingly, the driving forces of bio-geosystem function and stability under conditions of the variable abiotic environment have not yet been revealed, which is directly related to global warming and its ecological consequences. In the author's paradigm, experimental geoecology exactly contemplates the development of scientific and methodological bases of spatial functional monitoring of forests based on empirically established local and regional landscape-ecological connections, which are considered the mechanisms of metabolic responses of forest ecosystems to particular climatic trends. The problem of monitoring has not yet been developed in this respect, first, because of the absence of the necessary factual basis and, second, because the sufficiently strict methods for local and regional ecological prediction proper have not yet been developed. We have solved both of these problems, and exacting readers will estimate our success.

The monograph consists of 17 chapters combined into 7 sections. The *author's paradigm of experimental geographical ecology* described in these sections is an empirically substantiated, logically ordered, and internally consistent scientific and methodological construction. The author has worked in the field of geographical ecology for the past 40 years; he has put forward and developed the following scientific and methodological concepts: (1) the principles and methods of discrete empirical-statistical modeling of the spatial organization of different-order geo(eco)systems, as well as construction of the predictive models of their climate-genic transformations; (2) the thesis of geographical ecotones as high priority objects for studying human effects on nature; (3) the numerical methods of regional and local landscape-ecological prediction; (4) the regional paleo-prediction concept (by the example of the Volga River basin) considering the forecasted ecological-geographical scenarios and their paleogeographical analogs as a single regional system of global environmental changes; and (5) the topo-ecological prediction concept "Global Changes at the Local Level" as a scientific and methodological basis of geosystem monitoring.

In addition, the experience of using the methods of landscape ecology in the assessment of the biological cycle, carbon balance of forest ecosystems, and biotic regulation of the carbon cycle under climatic changes were stated. In this context, new propositions of the theory of stability of natural ecosystems were proposed and the methods for calculating functional stability of local and zonal-regional forest communities based on discrete parameters of the biological cycle were developed. Then, the basic and predictive landscape-ecological modeling of high-mountain ecosystems in the Central Caucasus was performed to provide further development of the regional aspects of physics of the biosphere and creation of the scientific and methodological basis of high-mountain monitoring.

Other sections of the monograph are devoted to some urgent ecological-geographical problems. The first problem concerns the prospects of using biosphere reserves as objects of regional and geosystem monitoring. The analysis was performed by the example of the By-Oka-Terrace Nature Biosphere Reserve. In addition, the evolutionary landscape-ecological concept is presented as a predecessor of the new field of complex physical geography and geoecology – evolutionary landscape science. The concept is based on the empirical-statistical models of organization and climate-genic dynamics of boreal forest ecosystems in the insular-arc and marginal-continental sectors of the Pacific Ocean mega ecotone of Northern Eurasia.

Addressing this work to the broad circle of experts in physical and biological geography, the author sought to make the developed landscape-ecological models and their substantial analysis the effective formalized tools for analysis and prediction in geographical ecology, using rather simple methods of discrete mathematics for the processing and generalization of empirical data obtained from traditional field and cameral landscape studies.

ACKNOWLEDGMENTS

This book was supported by the Russian Foundation for Basic Research (projects № 94–05–17–636, 96–05–64233, 01–05–64108, 04–05–96506a, 11–05–00575, 14-05-00032 and 18-15-00023).

The author is also grateful to anonymous reviewers and to the editor for constructive comments that have substantially improved the quality of this manuscript.

LIST OF SPECIAL TERMS MENTIONED IN THE BOOK

Absorption ≡ Adsorption
Antropogenic
Alfe-humus
Actualistic
Aridization
Biocosus
Biocoenotic
Biogeocoenosis
Biogeocoenology
Biogeosystems
Biochorological
Biogeo-horizon
Bonitet
Cartogramming
Chorological
Chorometric
Cisural
Composition
Conformation
Climate-genic
Coenotic
”Core of the typicallness”
Deluvial
Deluvium
Demutational
Desuccesional
Ecogenetic
Eco-mass
Ecotonization
Ecto-genic
Edaphetopes
Eemen
Endo-ecogenic

Endo-genous
Entomopests
Extra zonal
Facie
Factor
Fersillization
Fluvio-glacial
Floro-coenotic
Foots
Geochores
Geotopic
Geo-ecological
Geoecotone
Geo-complex
Geo-component
Geo-synergetic
Gleyization
Gleyic
Goltsy
Homeostacity
Horological
Humidization
Hydro-edaphic
Hydroedaphotop
Hydromorphity
Hydromorphic
Isogiets
Lithomorphity
Lithogenically
Lithomass
Mari
Macro-substrate
Meso-catena
Macrobolite
Meso-tropes
Mesobolite
Microbolite
Mort-mass
Morphostructure
Morphosculpture
Nemorouse

Nival
Nonpodzolized
Orgraph
Oceanisity
Ouvals
Paleo-prognostic
Paludification
Phytobiota
Phytocoenosis
Pleiad
Phytocoenomers
Prairified
Prairification
Phytosphere
Phanerophytes
Placor
Polysystem
Paludification
Paradynamic
Paleo-forecasting
Peneplanation
Pecit-bog
Petrophyte
Phytocoene-genetic
Podzolized
Podburs
Polyzonality
Proluvial
Rendzina
Savannization
Subors
Sub-zonal
Steppified
Sub-ripe pine
Savannization
Steppification
Semicontinuities
Sinchoric
Sod-podburs
Soddy podzolic
Sub-aqual

Stows
Steppified
Szyrt
Typomorphic
Topo-ecosystem
Trophisity
Topological
Trophic

PART I.

INTRODUCTION TO EXPERIMENTAL GEOECOLOGY

CHAPTER 1

PROBLEMS AND METHODS OF EXPERIMENTAL GEOGRAPHICAL ECOLOGY: A SHORT REVIEW

Abstract

The author's paradigm of experimental geographical ecology and its core – landscape ecology – have been set forth. The empirical statistical models created by the author and the ecological geographical concepts developed on their basis are described. They disclose the mechanisms of formation of regional- and local-level landscape-ecological systems, their natural and anthropogenic dynamics and evolutionary trends. The landscape ecological analysis was performed using specific examples and empirical simulation techniques for the estimated prognostic situations. In the constructed models, geographical ecology acquires an effective formalized tool for analysis and prediction using the methods of discrete mathematics for the processing and generalization of bulk empirical data obtained from field and laboratory landscape studies.

1.1. The subject of experimental geoecology

The ecological experiment includes five successive stages: hypothesis, planning, implementation, statistical analysis, and interpretation (Helbert 2008 a). At the same time, the planning and peculiarities of implementation of the experiment are of primary importance: they equally determine the soundness and results of the research. Statistical analysis must

> "… increase the accuracy, expressiveness, and objectiveness of presentation and interpretation of results" (ibid. 12).

Hereinafter we will give an account of the strategy of landscape-ecological experiment in the context of the development of a scientific and methodological basis for geosystem monitoring of global changes in the