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RESEARCH ARTICLE

Bolreal ecotone of the East-European Plain: Empirical statistical modeling

Erland G. Kolomyts

Samara Research Center of Russian Academy of Sciences, Institute of Ecology of the Volga River Basin, Togliatty 445003, Russia

Correspondence to: Erland G. Kolomyts, Samara Research Center of Russian Academy of Sciences, Institute of Ecology of the Volga River Basin, Togliatty 445003, Russia; Email: egk2000@mail.ru

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Abstract: The solution of multipurpose tasks of ecological forecasting may depend to a great extent on the results of system analysis of nature-territorial structures, which are most sensitive to external effects including anthropogenic. The scientific search in this direction focuses more and more attention on the natural boundaries – both individual and complex, where the most significant natural or anthropogenic shifts in the structure and function of geo(eco)systems are observed. Considering one or another natural boundary as a vector (connection, cascade, para-dynamical, *etc.*) landscape system with a clearly defined spatial polarization of its different properties, we obtain a "fast-flowing" model of state response and resistance of geo(eco)systems to the action of certain ecological factors. The study of the structural-functional organization of natural ecosystems at the geographical ecotones is also of scientific and methodical importance, which is common with geo-ecology and, in addition, most important for regional and local landscape-ecological forecasts. Geographical ecotones are the most sensitive (and, in this sense, the least stable) fragments of natural-territorial mosaic. The boreal biogeographic ecotone of the Volga River basin is described as an example for considering the theoretical and scientific-methodical problems of geographical zonality: the fundamental ecological-geographical conception at the present-day stage of biosphere evolution associated with the global anthropogenic impact on the climate. A conception on regional bioclimatic system, characterizing climate-genic exo-dynamic characteristics of soil-vegetation "core" of natural com-plexes is presented. It can survey as a scientific-methodological base of paleogeographical reconstructions and landscape-ecological forecasts. Climate nishes of the phytocoenological and soil' units are the elements of bioclimatic system and the forms of display of soil-vegatation cover' hydrothermal stability during the changing climate. Zonal boundaries are considered as modern spatial analogs of the future landscape changes in time. The work dwells on the basic "trigger" mechanisms of zonal boundary formation at the interaction of background climatic signals and their refraction by local (mainly lithe-genic) factors.

Keywords: geographical zonality, boreal ecotone, landscape connections, chain reactions, empirical statistical modeling

1 The main provisions for the theory of geographical ecotones

The solution of multipurpose tasks of ecological forecasting may depend to a great extent on the results of system analysis of nature-territorial structures, which are most sensitive to external effects including anthropogenic. The scientific search in this direction focuses more and more attention on the *natural boundaries* – both individual and complex, where the most significant natural or anthropogenic shifts in the structure and function of geo(eco)systems are observed. Considering one or another natural boundary as a vector (connection, cascade, paradynamic, *etc.*) landscape system [1–4]. With a clearly defined spatial polarization of its different properties, we obtain a "fast-flowing" model of state response and resistance of geo(eco)systems to the action of certain ecological factors.

The systematic approach to the study of natural environment organization would be expediently realized by the example of marked and large enough bio-geographical and landscape borders – *ecotones*, which are the zones of transition between contrasting natural environments. These are the most dynamic structural/functional subdivisions of the biosphere, with enhanced "tension" of matter-energy interactions and with the most pronounced manifestation of new, evolutionary tendencies in the environment [5–9]. Landscape contents are a critically important element of the wide range of modern notions of ecotones [10]. As a result, a concept of landscape-ecotone, or geo-ecotone, has been developed [11].

The lateral fluxes and the respective inter-complex connections along geo-ecotones create the spatiotemporal order of natural complexes at all hierarchical levels: from continental or oceanic sector to landscape facies [4]. Longitudinal climatic sectors or morphotectonic belts, on the one hand, and soil-geochemical catenas with the respective phytocoenotic spectra, on the other hand, comprise the two extreme levels of the hierarchy of geographical ecotones.

At the same time, a simple identification of a geo-ecotone with any natural boundary is unlikely to have meaningful meaning. Based on the initial meaning of the concept of ecotone (Greek *oikos* – house, *tonos* – voltage), the geographical ecotone should be understood only as of the border zone, strip, line through which the interaction between neighboring territories is carried out. Geo-ecotones are characterized by increased horizontal landscape connections that unite these territories into vector landscape structures. A geo-ecotone can be thought of as a spatial alternative to a geo-ecotope – a type of location of any taxonomic rank, the properties of which serve as guiding features in identifying genetically or typologically homogeneous geosystems of a given hierarchy level. D.L. Armand [12] called geo-ecotones "nucleuses of typical" landscapes. In them, the geo-field gradients are minimal and therefore the density of horizontal bonds is the smallest.

The higher the functional integrity of the para-genetic (connection, cascade, *etc.*) geosystem, the more closely its links are interconnected, the faster and more anthropogenic impact propagates in the direction of connecting geo-processes. On the other hand, the more intense the flow, the more pronounced the spatial structure of such a lateral system. Consequently, the study of geo-ecotonic structures of different taxonomic levels creates the necessary prerequisites for geosystem monitoring of vast territories. The velocities of points are generally determined by the degree of heterogeneity of the interacting natural environments and the corresponding gradients of the energy fields. For this reason, the principle of contrast at all hierarchical levels, in contrast to the principle of homogeneity, which corresponds to the traditional approach to the study of natural interactions and regionalization of territories, should become the methodological basis for the identification and analysis of such geosystems.

One more important circumstance of a methodological nature should be noted. In contrast to homogeneous geosystems, vector or "synergistic" natural complexes are closest to the technical systems in their structural features and functioning methods, therefore, their knowledge in the first approximation can be reduced to the study of relatively simple processes of material-energy metabolism, which are considered with engineering (in the broad sense) point of view [13]. This allows for the analysis of vector natural-territorial structures to make wider use of modeling methods developed for technical objects. An example is an experience of using the conceptual apparatus of reliability theory to calculate partial measures of the stability of a geosystem [14]. Stability is evaluated by the behavior of a natural component and is associated with the concept of failure - events of the state of this component leaving the area of homeostasis.

The overwhelming majority of studies, both in Russia and abroad, are concerned with local phytoecotones [5, 10, 15] due to the problems of discreteness and continuum of vegetation cover, biodiversity, as well as the distribution of species and communities along the gradients of abiotic factors and at the interface between contrasting natural environments. Various ecotone classification schemes developed in this context were considered in the work [10]. It is also known about the studies of ecotones of the higher taxonomic rank, e.g., zonal geo-ecotones and oro-ecotones [4, 8, 9, 16–18].

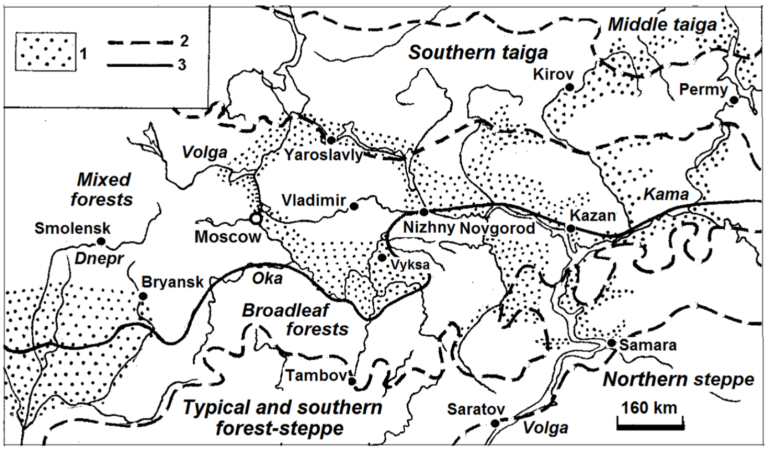
Geoecotones, as the most sensitive fragments of the natural-territorial mosaic to external signals, should serve as primary objects of study of the human impact on the environment. The fact is that the impetus for the transformation of geo (eco-) systems and their transition to a qualitatively new state is the aggravation, first of all, of inter-complex (horizontal) landscape connections [19], which are most characteristic of geographic ecotones [8]. The activation of lateral natural interactions during periods of violation of the previously achieved (to one degree or another) stability of natural ecosystems under the influence of new climatic signals is the primary cause and driving force of those landscape-ecological rearrangements that were in the past and which are expected in the future. Thus, lateral relations and connections become the subject of an independent paleo-predictive study in geo-ecotones; the parameters of these links should be directly included in the corresponding calculation models.

The problems of studying geo-ecotones are closely related to the development and degradation of landscapes, the driving forces and rates of the evolutionary process, taxonomic and age relationships of the structure and functioning of geosystems, their ontogeny, and phylogenetic changes, and finally, the regularities of the formation of landscape connections on land. In essence, those scientific and methodological problems that relate to the very origins of the natural-territorial organization of the continental part of the geographic shell of the Earth should be considered.

2 Landscape-ecological particularity of the East-European boreal ecotone

In Northern Eurasia, the largest bioclimatic and landscape-zonal transition zone is a broad boundary frontier between the boreal (mainly taiga-forest) and sub-boreal (forest-steppe and steppe) belts of plant formations.

The frontier stretches from the Baltic Sea to the East Sayan and Lake Baikal [14] and then, after a break, to Inner Mongolia. This *transcontinental boreal ecotone* is a vector (connection) geosystem of the highest, or belt, rank. The objects of our study were coniferous-forest and coniferous-broadleaf natural complexes close to the zonal boundary between sub-taiga and southern forest-steppe in the center of the East-European (Russian) Plain. The forest zones of the headwater of the Volga River basin are entirely included in the East-European branch of the Eurasian boreal ecotone (Figure 1). Being *the southern outpost of the boreal belt*, this forest cover is in conditions close to critical and therefore very unstable, which advances the problem of preservation and reproduction of forest resources of this territory (industrial "core" of the European Russia) among the ecological problems of high priority.



1: forested outwash lowland; **2**: boundaries of nature zones and subzones; **3**: Main Landscape Border of the Russian Plain, by Mil'kov [4].

Figure 1 Landscape-zonal structure of boreal ecotone on the Russian Plain

The boreal ecotone is determined first of all by the most important climatic border – the transfer of the warmth/humidity ratio across 1, which radically changes the energy potential of main natural processes: weathering and soil formation, transformation and migration of substances, formation, and development of biocoenoses [21]. Within broad-leaved forests and a typical forest-steppe, a spectrum of contours of the annual radiation balance of 1450–1850 MJ/m^2 (35–45 kcal/cm^2) passes. It serves as an important boundary dividing two thermal zones: northern (boreal) with insufficient heat supply, with sufficient and excessive moisture, and southern (sub-boreal), with sufficient heat supply, but with a lack of moisture. Especially it should be emphasized the change in the boreal ecotone of the roles of heat and moisture as background limiting factors of the structure and productivity of phytocoenoses. In the boreal zone, an increase in atmospheric moisture leads to a decrease in the productivity of ecosystems, in the sub-boreal zone, on the contrary, to its increase [21].

As can be seen from the climate-diagram of Isachenko [22], the zonal spectrum of the northern wing of the boreal ecotone (change of the southern taiga to mixed and broad-leaved forests) is due to an increase in heat supply, and the southern wing (transition to the forest-steppe and northern steppe) – due to a decrease in atmospheric moisture. Accordingly, an increase in the primary productivity of zonal plant formations in the first case occurs due to an increase in heat supply, and in the second case, with an increase in moisture supply. One should stress the changing on the ecotone of the roles of warmth and humidity as limiting factors of bio productivity. The increase of production of zonal plant formations in the boreal belt is due mainly to the growth of warmth, and in the sub-boreal one – at the increase of humidity. In the first case, the growth of humidification results in a lower productivity of ecosystems, while in the second case, on the contrary, in its increase. Consequently, in the transition zone there must occur the reconstruction of the principal scheme of territorial distribution of zonal (flat interfluve) and intrazonal natural complexes. Therefore the study of landscape-zonal structure of the boreal ecotone is of great importance for differentiated assessment and forecast of resistance of geo(eco)systems to natural (mainly climatic) and anthropogenic factors.

Our landscape-ecological studies in the Middle Volga region showed [23] that this hydrothermal fracture occurs already near the southern boundary of the sub-taiga zone; therefore, not only coniferous, but also broad-leaved forests here are in conditions of increasing moisture deficit to the south, which is a decisive factor in their potential instability. This advances the problem of preservation and reproduction of forest resources of this territory (industrial "core" of the European Russia) among the ecological problems of high priority.

Bioclimatic contrasts between forest and forest-steppe territories on the boreal ecotone are enhanced by geological and geomorphological factors, bringing the difference between them to the level of physical and geographical provinces. Ecotone separates the two largest geomorphological (and, correspondingly, physical-geographical) regions of the Russian Plain: 1) northern, mostly accumulative, with a relatively young relief formed by planted forms of glacial and ancient alluvial accumulation; 2) southern, erosion-denudation, and erosion-accumulative, with an older, and therefore more mature relief (Figure 2).

Figure 2 Fragment of the main landscape border of the Russian Plain, Oka River Valley in the By-Oka-Terrace nature reserve area. (In the foreground (right bank of the Oka river) is broad and small leaved forest; in the background is mixed forest of the By-Oka-Terrace Reserve.)

The Russian Plain, including the main catchment of the Volga river basin, has a rather pronounced "polarization" of its geomorphological skeleton [24]. The morph structure of modern landscapes here finally formed in the Neogene, when, as a result of differentiated tectonic movements against the background of a general elevation of the Paleogene surface of the Russian Plain alignment, the Middle Russian and Volga Uplands arose, and the Verkhne-Volzhsky elevated ridges were formed. Active exogenous processes divided the increases into a series of reservoir elevations and ridges, while the depressions were deepened and widened [25, 26]. In the Pleistocene, due to the accumulation of thick (up to 150–200 m and more) strata of glacial and fluvioglacial deposits, mainly in the lowlands, and further denudation of reservoir elevations, the main elements of morpho sculpture took shape, emphasizing the vector ("polarity") of the modern geomorphological framework of the territory and thereby predetermining the system of regional and local landscape conjugations (watershed-slope-valley).

Being inherited from the geological past, these morpho-structural contrasts are also supported by modern tectonic movements throughout the sub-latitudinal strip of the Oka–Volga–Kama river valley system. The northern left-bank low-lying taiga-forest areas descend with speed up to 1.5–2.0 mm/year), while the forest-steppe and steppe regions of the elevated Right Bank tend to rise (up to 2.0–2.5 mm/year). Thus, the indicated system of river valleys undergoes a sharp, inversion change in tectonic processes, and this change is reflected in the depth of groundwater, which characterizes the degree of drainage of the territory. As a result, the regimes of soil and soil waterlogging are maintained throughout the low-lying forest Oka–Volga Left Bank, on the one hand, and the natural drainage is intensified, with erosive dissection of the surface areas of elevated forest-steppe Right Bank, thereby increasing their aforementioned "predisposition" to anthropogenic warming, on the other hand.

Thus, the cardinal bioclimatic changes on the Boreal ecotone of the Russian Plain are accompanied by drawing together of quite several component boundaries; their combination resulted in distinguishing the *Main Landscape Border of the Russian Plain* [4], which is the landscape "core" of the boreal ecotone (see Figure 1 and 2).

Overlapping of potential ecological niches of zonal vegetation types on the boreal ecotone causes an inevitable competition between plant species and communities [20, 27]. As a result, each zonal boundary becomes a "trigger belt – hysteresis loop" (see below), where both members of the competing pair of zonal communities may be quite stable. This is enabled by the forefront factors of landscape lithogenic basis – relief and composition of soil-forming rocks. The lithogenic basis brings about the territorial interpenetration of frontier geo(eco)systems, thus creating a more mosaic character of the trigger belt. As a result of the vertical differentiation of plain landscapes [4], a two-member complex is formed underlining the territorial polarization of the ecotone: sandy fluvioglacial and ancient alluvial low-cut lowlands (e.g., Pripyatsko-Desninskaya, Oksko-Moshinskaya, Nizmennoye Zavolzhye), on the one hand, and high loamy erosion-denudation plains (Central Russian Upland, Privolzhskaya, Vysokoye Zavolzhye), on the other hand. Boreal ecosystems (mainly pine-forested lowlands) advance southwards across outwash lowlands (see Figure 1), while sub-boreal (oak-grove and forest-steppe, where they remain) – across loamy uplands.

The system of chain reactions in inter-component interactions associated with the transition from north to south through the main landscape boundary of the Russian Plain is shown in Figure 3, which does not require a special explanation. It is only worth noting the main thing in these reactions: the change of some landscape-zonal systems by others on the boreal ecotone is not a purely climatic phenomenon: it occurs as a result of a rather diverse oro-climatic interaction, where water-thermal and litho-dynamic flows are closely interconnected, and background hydro-climatic The conditions and topography with surface deposits turn out to be equally powerful environmental factors, so it seems embarrassing to highlight the priority role of any of them on a regional scale.

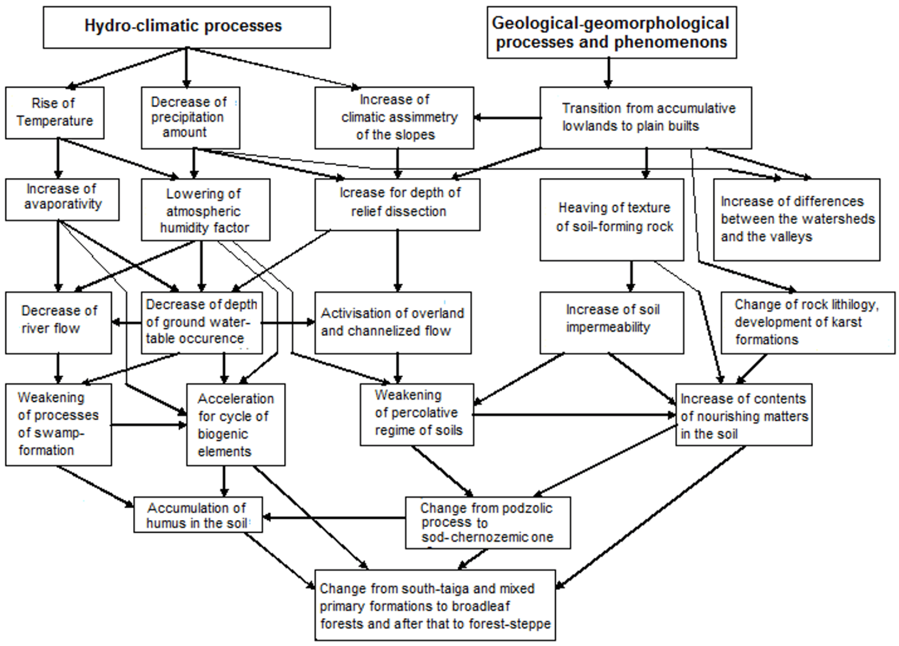


Figure 3 System of chain reactions in geo-component correlation under the crossing through Main Landscape Border of the Russian (East-European) Plain

Ecotone is known to be [28] quite an independent subunit of the biosphere, often differing from adjacent homogenous systems in a high complexity of the coenotic structure and higher bio productivity. Such structure-function features are fully characteristic of the boreal ecotone [26]. One should stress the changing on the ecotone of the roles of warmth and humidity as limiting factors of bio productivity. The increase of production of zonal plant formations in the boreal belt is due mainly to the growth of warmth and in the sub-, boreal one – at the increase of humidity [21]. In the first case, the growth of humidification results in lower productivity of ecosystems, while in the second case, on the contrary, in its increase. Consequently, in the transition zone, there must be the reconstruction of the principal scheme of territorial distribution of zonal (flat interfluve) and intra-zonal natural complexes of the local level. Therefore, the study of the topological structure of the boreal ecotone is of great importance for differentiated assessment and forecast of resistance of geo(eco)systems to natural and anthropogenic factors.

On the boreal ecotone, the restructuring of landscape, phyto-coenological, and soil areas begins, and new evolutionary trends in the natural environment arise here. Changes in the ratio of heat and moisture in this transitional band, caused by background climatic shifts, can entail a significant environmental change – a change in the sign of the relationship between the structure of natural ecosystems and their productivity with the main landscape and geophysical parameters. Figuratively speaking, considering the behavior of landscape-zonal systems on the boreal ecotone in the past, present, and future, the researcher gets into his hands a "fast-flowing" model of the regional manifestation of global changes in the natural environment.

The increased sensitivity of the boreal ecotone to external influences is caused, first of all, by the very narrow framework of the ecological space, within which a relatively quick and sharp change of natural zones occurs. As shown by the hydrothermal ordination of zonal types of landscapes [22], within the temperate zone, steppe, forest-steppe, broad-leaved, mixed, and coniferous forests coexist in the ranges of sums of biologically active temperatures of 1500–20000 and the Vysotsky–Ivanov's annual humidify factor (the ratio of annual precipitation to annual evaporativity) of 0.7–1.0, i.e., in rather narrow ranges of hydrothermal space.

Hence the inevitable mutual overlap of the climatic niches of most zonal systems on the boreal ecotone. In terms of temperature sums, this overlap is usually the smallest, which indicates the thermal regime as the leading spatially differentiating factor, while niches overlap much more in annual precipitation. Therefore, changes in the zonal structure of the boreal ecotone should be associated primarily with background thermal signals.

Overlapping of potential ecological niches of zonal vegetation types on the boreal ecotone causes an inevitable competition between plant species and communities. As a result, each zonal boundary becomes *a trigger systems with hysteresis properties*, by definition [29], where both members of the competeing pair of zonal communities may be quite stable. As a result of the vertical differentiation of plain landscapes, a two-member complex is formed underlining the territorial polarization of the ecotone: sandy fluvial-glacial and ancient alluvial low-cut lowlands, on the one hand, and high loamy erosion-denudation plains, on the other hand. Boreal ecosystems (mainly pine-forested lowlands) advance southwards across outwash lowlands, while sub-boreal (oak-grove and forest-steppe, where they still remain) - across loamy uplands.

Such ecosystems primarily bear the stamp of economic impact (clear cuts, grazing, plowing land, irrigation and drainage measures, industrial construction), which irreversibly change the structure of the thermal and water balances of territories towards aridization, and with them the ratio heat and moisture as the main property of zoning.

The study of structural-functional organization of natural ecosystems on the zonal ecotones has also scientific and methodical significance, which is common with geo-ecology and besides most important for the regional and local landscape-ecological forecasts. Geographical ecotones are the most sensitive (and in this sense the least stable) fragments of the natural-territorial mosaic, and investigation of the state and dynamics of geo(eco)systems on the zonal ecotone provides the researcher with a kind of "quick-running model" of the possible local response of natural complexes to background disturbances of the global climatic system or to large-scale hydro-technical measures taken by man.

This problem has a large enough practical aspect too. Ecological safety of large territorial subunits of the continental biosphere significantly depends on the state of the zonal-regional types of natural ecosystems, first of all, forest cover (Figure 4), and on the interrelations primarily of two competitive plant formations: forest and grassy.

Figure 4 South strip of mixed forest zone. Bisons in dark-coniferous/broadleaf forest of the By-Oka-Terrace Reserve

The above determines the importance of making the boreal ecotone as a sub-planetary boundary between forest and steppe an object of regional geo-ecological investigation. Therefore the problem of maintenance of forest ecosystems and reproduction of forest resources on the southern boundary of the temperate forest zone, where forest communities are present in the states close to critical, is among the fundamental ecological problems. It has always been of high priority for the East-European countries, where the wide transitional zone from forest to steppe, i.e., the zonal forest-steppe ecotone, is an industrial and demographical core of this large region. At the moment, more and more significance in the solution of this problem is gained by the questions of stability of natural ecosystems as a natural-historical basis of stable development of the region.

Boreal biogeographic ecotone of the Volga River basin is used as an example for consideration of theoretical and scientific-methodical problems of geographical zonality – a fundamental ecological-geographical conception at the present-day stage of biosphere evolution associated with the global anthropogenic impact on the climate.

The present investigation is also aimed at introducing the experience of cartographic modeling of regional scenarios of the nearest future of biosphere and their paleo-geographical analogs as a single system of global changes in the environment into the theory and practice of ecological prognosis. Probable ecological consequences of the forthcoming global warming for the boreal ecotone are assessed.

3 Regional landscape geophysical characteristics

This division states some results of information-statistical modeling of geo component interrelations on the territory of the boreal ecotone, revealing the patterns of mono system organization of natural ecosystems (landscapes) of the regional level. These patterns may be used for paleo-geographical and prognostic constructions in light of global climate changes. The analysis was based on 25 landscape-geophysical maps of the Volga River basin (1:2,500,000) reflecting different links of contemporary turnover and transformation of the solar energy and atmospheric moisture [18]. The whole territory of the basin has about 170 weather stations, 120 agrometeorological stations, and more than 300 observation points.

The map of contemporary primary productivity of natural ecosystems is built based on previously established regional empirical relations of bio productivity and annual radiation balance R_{ann} and Budyko radiation index of drought I_{drou} (Figure 5). The nomogram of relations is based on selected regions of the Russian Plain and adjacent plain and mountain territories that, first, have the known factual values of productivity of different zonal-regional plant formations from northern taiga to forest-steppe and northern steppes [30–32], and second, have the available data on radiation balance and atmospheric precipitation. The nomogram used more than 80 points with factual values of the primary bio productivity of landscapes, annual radiation balance, and annual precipitation total. To obtain the more leveled picture of bio productivity, particular values of the latter in the field of R_{ann} and I_{drou} were associated into pleiads (groups), and the mean value of productivity was calculated for each of them. Thereby we managed to obtain a family of straight lines in the range of 3–14 ton/ha that characterized an unambiguous dependence of productivity on specified geophysical parameters for each pleiade.

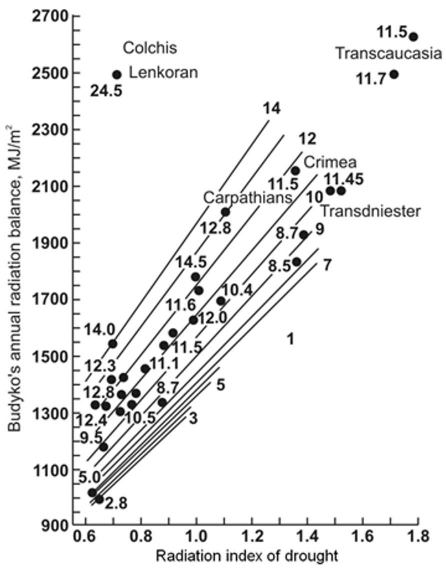


Figure 5 Distribution of primary productivity of natural ecosystems (t/h·year^{-1}) in coordinate field of annual radiate balance and radiate index of the drought for territory of Russian plain and its encirclement. (Legend. 2.8, 5.0, 9.5, *etc*.: average productivity values for a given galaxy of points.)

The total list of main landscape-geophysical parameters is presented in Table 1. As regards other geophysical parameters for the territory of the Volga river basin and its encirclement, we propose to calculate them by the following empirical formulas (for most of the parameters the coefficient of correlation R = 0.92–0.96 and only for $h^{sn}{}_{max}$, (W-50), (W-100) and r_{cold} it equals 0.82–0.87). These equations are next:

$$\Sigma t \geq 10^0 = 235.008 \cdot t_{\text{July}} - 2287 \tag{1}$$

$$E_0 = 1384 - 161.6 \cdot t_{\text{July}} + 6.245 \cdot t_{\text{July}}^2 \tag{2}$$

$$h_{\text{sn}}{}^{\max} = 0.0871 \cdot r_{\text{year}} - 5.083 \cdot t_{\text{Jan}} - 80 \tag{3}$$

$$I_{\text{drou}} = 0.0833 \cdot t_{\text{July}} - 0.0015 \cdot r_{\text{year}} + 0.4 \tag{4}$$

$$F_{\text{hum}}\,(1) = 0.016 \cdot r_{\text{year}} - 0.166 \cdot t_{\text{July}} + 3.2 \tag{5}$$

$$HTC = 5.353 - 0.2621 \cdot t_{\text{July}} + 0.0038 \cdot r_{\text{warm}} \tag{6}$$

$$STC = 4.506 \cdot h^{\text{sn}} \max - 0.8471 \tag{7}$$

$$I_{\text{snow}} = b \cdot T_{\text{stab}} \cdot h_{\text{ever}} \tag{8}$$

where b = 0.001 cm$^{-1}\cdot$ day; T_{stab} – the duration of the period with stable snow cover (day), h_{ever} – the average height of the snow cover for the same period (cm);

$$S_{\text{ann}} = 0.1028 \cdot r_{\text{year}} - 37.724 \cdot t_{\text{July}} + 794 \tag{9}$$

$$U_{\text{ann}} = 0.0776 \cdot r_{\text{year}} + 0.2079 \cdot S_{\text{sur}} - 38 \tag{10}$$

$$C_{\text{cont}} = (m_{\text{c}} + n_{\text{c}})\,/2;\;\; m_{\text{c}} = [1 - (t_i/t_0)] \cdot \cos\varphi;\;\; n_{\text{c}} = \left(r_0{}^{\text{year}}/r_i^{\text{cold}}\right) - 2 \tag{11}$$

Table 1 Information indicators of relationships of classes of plant formations and groups of soil types with landscape-geophysical characteristics of the Volga River basin

Geocomponent features (name and designation)	Vegetation		Soils	
	C(A;B)	*C(A/B)*	*C(A;B)*	*C(A/B)*
Annual total radiation, MJ/m^2, Q_{sum}	0.08	0.208	0.062	0.172
Annual radiate balance, MJ/m^2, R_{ann}	0.103	0.265	0.087	0.226
Average January temperature, t_{jan}	0.085	0.129	0.03	0.111
January latitude continantality, C_{janC}	0.142	0.372	0.101	0.29
Average July temperature, t_{july}	0.132	0.355	0.09	0.264
Sum of biological active temperatures , å t ³ 10^0	0.131	0.354	0.091	0.27
Length of the vegetation period, T_{veg}	0.193	0.374	0.15	0.326
Annual potential evaporation, E_0	0.154	0.35	0.109	0.266
Annual precipitation, r_{year}	0.103	0.299	0.066	0.219
Sum of the precipitation of the cold period, r_{cold}	0.047	0.164	0.034	0.121
Maximum height of the snow cover, $h^{\text{sn}}{}_{\text{max}}$	0.072	0.23	0.054	0.18
Sum of the precipitation of the warm period, r_{warm}	0.121	0.335	0.079	0.241
Annual evapotranspiration, E_{et}	0.025	0.085	0.018	0.062
Annual surface flow, S_{ann}	0.115	0.323	0.077	0.25
Annual groundwater flow, U_{ann}	0.147	0.381	0.082	0.263
Runoff coefficient, f	0.095	0.271	0.073	0.214
Depth of ground water-table occurrence, Z_{gw}	0.199	0.16	0.132	0.109
July soil moisture in stratum 0–20 cm , *W-20*	0.235	0.367	0.227	0.372
July soil moisture in stratum 0–50 cm , *W-50*	0.191	0.359	0.187	0.367
July soil moisture in stratum 0–100 cm , *W-100*	0.192	0.379	0.167	0.363
Budyko's radiate index of the drought, I_{drou}	0.117	0.328	0.076	0.244
Vysotsky-Ivanov's atmospheric humidity factor, F_{hum}	0.138	0.367	0.082	0.262
Hydrothermal coefficient, *HTC*	0.142	0.374	0.093	0.275
Snow-temperature coefficient, *STC*	0.086	0.262	0.064	0.212
Classes of the plant formations, *Plant*	–	–	0.11	0.303
Soil groups, *Soil*	0.111	0.315	–	–
Primary bio productivity, P_{prim}	0.074	0.182	0.049	0.123

$$C_{\text{JanC}} = \left(a^+_{\max} - a_i\right) / \left(a^+_{\max} - a^-_{\max}\right) \cdot 100\% \tag{12}$$

where $a_{max}{}^+$ and $a_{max}{}^{--}$ – maximal positive and negative anomalies of average January temperature on given latitude, and a_i – real anomaly in given point; July latitude continantality (C_{julyC}) is calculated by analogues formula, but with anomalies of parameter t_{july};

$$(W-20) = 0.0257 \cdot r_{\text{year}} + 0.0676 \cdot S_{\text{sur}} - 0.0136 \cdot E_0 + 0.8 \tag{13}$$

$$(W-50) = 0.0631 \cdot r_{\text{year}} + 0.1746 \cdot \text{S}_{\text{sur}} - 0.0231 \cdot E_0 + 7.6 \tag{14}$$

$$(W-100) = 0.0964 \cdot r_{\text{year}} + 0.3216 \cdot S_{\text{sur}} - 0.0802 \cdot E_0 + 33.5 \tag{15}$$

$$P_{\text{prim}} = 0.0139 \cdot r_{\text{year}} - 0.2064 \cdot t_{\text{July}} + 0.055 \cdot T_{\text{veg}} - 4.2 \tag{16}$$

$$T_{\text{veg}} = 5.6 \cdot t_{\text{July}} + 2.87 \cdot t_{\text{Jan}} + 102 \tag{17}$$

For the regions with t_{July} >19°:

$$F_{\text{hum}} = 12.09 - 0.9095 \cdot t_{\text{July}} + 0.0174 \cdot t_{\text{July}}^2 \tag{18}$$

$$HTC = 28.37 - 2.406 \cdot t_{\text{July}} + 0.0529 \cdot t_{\text{July}}^2 \tag{19}$$

The following small-scale maps of the East-European Plain territory were also used for the mathematical-cartographic analysis: geo-botanic, soil, soil-geochemical, the map of hydro-geological conditions, *etc.* [33]. Natural vegetation is defined on the level of classes of plant formations and soils – on the level of soil species groups.

4 Information statistical modeling of landscape inter-relations

By way of coupled analysis of landscape-geophysical maps for the territory of the Volga River basin using informational modeling [34–37], we have established the orderly system of statistic parameters characterizing spatial relations between hydrothermal attributes. These relations are focused on vegetation and soils, as well as on the primary bio productivity. The information-statistical analysis of empirical material was employed to uncover the landscape component interconnections (see above). The main parameters of these connections are as follows: (1) the *normalized coefficient of interrelation C(A;B)* of two attributes taken in pairs: considered object – phenomenon *A,* and effects on it factor *B* and (2) the *partial coefficient of connection C(ai /bj)* characterizing the closeness of interrelationship of individual classes (gradations) of these attributes. These gradations are marked in form of elements of the next sets: *A* = $\{a_1, a_2, \ldots, a_i, \ldots, a_n\}$ and *B* = $\{b_1, b_2, \ldots, b_j, \ldots, b_m\}$. Each phenomenon and each factor has a certain multitude of states.

The first parameter indicates the degree of general closeness of spatial interrelations between the attributes of forest ecosystem states. In the initial working matrix, the vector of states (gradations) of factor *B* forms lines, and the vector of states of phenomenon *the columns of A form*. The matrix cells contain probabilities, or frequencies, p_{ij} of co-occurrence (probability) of the given states of *A* and *B*. The sums by the columns and lines yield a priori (independent) probabilities *p(*a_i*)* and *p(*b_j*)*, respectively; they are used to calculate the values of conditional probabilities *p(*a_i */* b_j*)*. At the same time, a priori probabilities *p(ai)* characterize phenomenon *A* under the assumption of its absolute independence of factor *B,* when *p(*a_i */* b_j*)* = *p(*a_i*)*. The measure of the difference between the conditional and a priori distribution of *A* is the function *I(A/*b^j*)* equal to:

$$I\left(A/b_j\right) = H(A) - H\left(A/b_j\right) \tag{20}$$

$$H(A) = -\sum_{i=1}^{N} p\left(a_i\right) \log_2 p\left(a_i\right) \tag{21}$$

$$H\left(A/b_j\right) = -\sum_{i=1}^{N} p\left(a_i/b_j\right) \log_2 p\left(a_i/b_j\right) \tag{22}$$

Parameter *I(A/*b_j*)* is the measure of the force of the general effect of this factor on the phenomenon. The higher is the *I(A/*b_j*)* value, the more rigid is their connection. Parameters *H(A/*b_j*)* and *I(A/*b_j*)* are calculated for each line of the working matrix. The total amount of information, which is transferred from factor to phenomenon and characterizes the closeness of their connection, is equal to:

$$T(AB) = \sum_{j=1}^{m} p\left(A/b_k\right) I\left(A/b_k\right) \tag{23}$$

The amount of information is estimated in binary units (bits); however, it is more convenient to use the relative measures of connection expressed in quotas of 1. In the present study, the normalized coefficient of interrelation has been used:

$$C(A;B) = \frac{2^{T(AB)} - 1}{2^{H(\min A,B)} - 1} \tag{24}$$

Here, $2^{T(AB)}$ is the number of general states of *A* and *B*, while *H(A)* and *H(B)* are the common measure of the diversity of characters *A* and *B,* respectively. The coefficient of information receive *C(A/B)* has itself certain meaning [36]:

$$C(A/B) = \frac{T(AB)}{H(A)} \tag{25}$$

Parameter *C(A;B)* was used for the construction of generalized information-statistical models of landscape-ecological connections in the regional and local ecosystems. Table 1 shows the information indicators of space relationships of plant formations and soil groups with landscape-geophysical characteristics of the Volga River basin.

5 Chain reactions in the regional landscape-geophysical relations

The information-statistic model (or-graph) in Figure 6 presents by far not all inter-component connections but only those that are important for the understanding of the system-forming role of different geo-components and identification of the main relation channels that we consider transducers of external impacts (both natural and anthropogenic). We have got a model of chain reactions of the regional landscape-geophysical system of the Volga River basin to hydro-climatic disturbances. The model easily follows the main directions of transduction of external signals and estimates the relative speeds of their transmission along the chain of inter-component connections, using the values of the normalized coefficient of coupling *C(A;B)* phenomenon A with factor B, according to [37], or the coefficient of information reception *C(A/B)* by the phenomenon from the factor, according to [36]. These coefficients implicitly characterize the width of the relation channel and the corresponding rate of chain reaction.

The model clearly demonstrates the prevailing effect of energy and moisture exchange in the warm period as compared with the same processes of the cold period, which supports the known regional peculiarity of the hydro-climatic regime of the entire territory of the East-European Plain [18]. The summer inflow of solar energy and summer atmospheric precipitation are the two starting beginnings of landscape-geophysical organization of this territory, of the formation of its zonal and longitude-sector structure. This is evidenced by doubling chains of rather strong connections that originate from them (with *C(A;B)* = 0.20–0.25 and more). Recall that according to [37], the parameter *C(A;B)* = 0.194 corresponds to a correlation coefficient of 0.6–0.7.These parameters serve as primary edificators and somehow or other determine all other landscape-geophysical characteristics.

The first echelon of re-translation (transformation) of external climatic signals is formed by thermal characteristics of the vegetation period and the warm period of the year as a whole: the mean July temperature, the total of biologically active temperatures, and annual evaporation determined almost solely by the summer season. At the same time, these parameters have obvious edificatory properties, which is clearly shown by the orgraph itself: they have much more outgoing than incoming arrows.

The complex landscape-geophysical indices – radiation index of aridity, annual coefficient of humidification, hydrothermal coefficient, snow-temperature coefficient – reflect the ratio of warmth and moisture (both for the whole year and for the warm and cold periods). Along with the coefficient of winter latitudinal continentality, they form an intermediate series of re-translators – the second echelon of connections that creates internal points of information receipt and transmission. At the same time, the annual coefficient of humidification is the most sensitive to the factors of external climatic effects. It has the greatest number of incoming and outgoing, strong and moderate, binary connections. It should be noted, however, that the annual and summer complex climatic indices are derived from initial hydrothermal parameters – radiation balance and precipitation, therefore the main channels of external impacts pass through them with *C(A;B)* > 0.2. Meanwhile, I_{Bud} and the hydrothermal coefficient (HTC) are efficient re-translators as well.

The most narrow conducting channels of relations prove to be hydrothermal parameters of the cold period: r_{cold}, t_{Jan}, $h^{sn}{}_{max}$, snow-temperature coefficient (STC), C_{cont}. Consequently, changes in the winter climatic conditions cannot anyhow significantly affect the total landscape-geophysical structure of the given territory.

The third echelon of transformation of external signals (the third series of re-translators) is formed by characteristics of the water balance output: the annual surface and underground runoff and the runoff coefficient. The runoff parameters are determined directly by the coefficient of humidification and much less depend directly on the temperature regime or atmospheric precipitation proper.

The closing links in the system of regional connections of hydrothermal parameters are hydro-edaphic attributes: summer reserves of productive moisture in soil layers 20, 50, and 100 cm thick. The moisture content in the upper soil horizons is the most sensitive to external effects. It is directly determined mainly by evaporation and surface runoff (*C(A;B)* is equal to 0.222 and 0.202, respectively). Moisture reserves in the middle and lower soil horizons are more invariant and regulated by another set of factors. Their dependence on evaporation is retained (*C(A;B)* = 0.170–0.178), and there appear quite relevant connections with precipitation of the warm period, underground runoff, and the runoff coefficient (0.124–0.154). Rather close connections of *(W-20)* and *(W-50)* with $F_{hum}$and *HTC* (*C(A;B)* = 0.168– 0.213) points to the fact that the distribution of summer moisture content in soils of the Russian Plain is zonal as a whole. This allows us to predict, via hydro-edaphotops, the general shift of zonal conditions of the territory by the specified scenarios of regional climate changes.

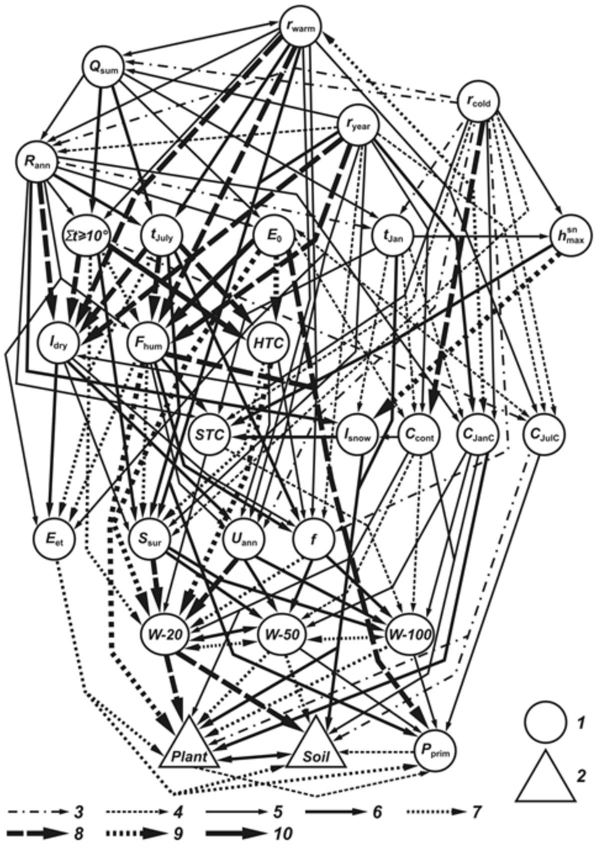


Figure 6 East-European Plain; Hydro-climatic block of landscape-ecological relations. (Geo-component blocks: 1: hydrothermal; 2: soil-vegetable. Normalized coefficient of contingency of geocomponent features; 3: 0.050 and less; 4: 0.051–0.080; 5: 0.081–0.120; 6: 0.121–0.160; 7: 0.161–0.200; 8: 0.201–0.240; 9: 0.241–0.300; 10: more than 0.300.)

Hydro-edaphic attributes are also determined by the lithe-genic basis of plain landscapes: first of all by a combined effect of morpho-structure and morpho-sculpture (for the soil layer of 0–20 cm *C(A;B)* = 0.176) and, to the lesser extent, the true altitude of a place and mechanical composition of soil-forming substrates (the coefficient of relationship is about 0.085).

Thus, summer reserves of productive moisture in soil are the most representative geophysical indicator of the situation in zonal-regional geosystems of plain territories. Moreover, while integrating the whole system of heat and water turnover in landscapes, hydro-edaphic attributes are the most powerful ecological factor of direct action, which predetermines the territorial distribution of not only soil species but also zonal-province types and subtypes of the vegetation cover (see Table 1). At the same time, the effect of moisture content of the upper soil horizons is the most significant: the coefficient of their connection with vegetation and soils exceeds 0.22–0.23 but is 1.5–2-fold lower for the most effective heat-energy attributes of surface-atmosphere (the mean July temperature and annual evaporation).

Vegetation and soils are equifinal links of chain reactions in geo(eco)systems. Typically, hydro-climatic factors affect them more effectively than lithe-genic factors. The parameter *C(A;B)* reaches 0.16-0.23 in the first case and does not exceed 0.07–0.12 in the second case. The high sensitivity of soil-vegetation cover of the Volga River basin to century and super-century changes in the climate is obvious, supported by the history of vegetation of this territory in Holocene [38,39]. Meantime, the soil is much more independent of hydrothermal conditions than vegetation; only their coupling with summer edaphic humidification is equally high.

The relative contribution of the main landscape-geophysical factors to the distribution of classes of plant formations (Y_1) and groups of soil species (Y_2) can be expressed as the following polynomes, where coefficients at the arguments are values of the parameter *C(A/B)* (see Table 1) and the remainder term *Xi* denotes unaccounted factors (the total of all coefficients is 1):

$$Y_1 = 0.129 \cdot t_{\text{Jan}} + 0.355 \cdot t_{\text{July}} + 0.164 \cdot r_{\text{cold}} + 0.335 \cdot r_{\text{warm}} + 0.017 \cdot X_i \quad (26)$$

$$Y_2 = 0.111 \cdot t_{\text{Jan}} + 0.274 \cdot t_{\text{July}} + 0.121 \cdot r_{\text{cold}} + 0.241 \cdot r_{\text{warm}} + 0.123 \cdot P_{\text{prim}} + 0.109 \cdot Z_{\text{gw}} + 0.021 \cdot X_i \quad (27)$$

The highly irregular contribution of hydrothermal conditions of different periods of the year to the variability of soil-vegetation cover is evident. The combined effect of summer temperatures and precipitation is almost 2.5-fold more efficient than the effect of the same winter characteristics, being much higher for vegetation than for soils (69% vs. 52%). Consequently, natural ecosystems must experience the maximal structure-functional rearrangements with the background climatic changes during the vegetation period – the time of the most complex and intensive biocoenosis processes.

Judging from the values of *C(A/B)*, one may also suggest that spatial variations of vegetation and soils are determined by the combined effect of *HTC* and *STC* for 63% and 49%, respectively. Their total effect is almost two-fold more efficient than the effect of annual coefficients: $F_{hum}$and I_{drou}. Thus, it is expedient to create paleogeographical and prognostic landscape-ecological scenarios based on temperature and precipitation changes not for the whole year, but the warm and cold periods separately.

Finally, the whole system of chain reactions is closed by the primary bio productivity of regional geosystems P_{prim} as an integral parameter of their functioning that is known [30] to form the final link of landscape-geophysical connections. It is important to mention a very weak connection of the parameter P_{prim} with the structural characteristics of the soil-phytocoenotic core of geosystems (*C(A;B)* = 0.05–0.07). Bio productive process, being largely (to a great extent) invariant to phytocoenotic structure and soil morphology, is almost directly connected with thermal conditions of the vegetation period, as well as with the annual and summer coefficients of atmospheric humidification. This must considerably facilitate the paleo-prognostic calculations of the primary bio productivity of natural ecosystems.

The initial climatic parameters of global and regional paleo-reconstructions and prognoses are, as is known, the mean January and July temperatures and the annual amount of precipitation, sometimes with the partition of the latter to precipitation of the cold and warm periods. We have mapped the above parameters for the territory of the Volga River basin according to the information [39,40] about the optima of the Mikulino (Eemean) interglacial period and Holocene optima, as well as the data from the global climatic prognosis by the model of GISS (Goddard Institute of Space Science) for the periods of 2050, 2075 and 2100 [40] transformed on our request by G. V. Menzhulin and S. P. Savvateev for the regional level. This was the basis for the calculation of all other (derivative) hydrothermal parameters, both particular and complex. The paleo-prognostic calculations used the contemporary statistical relations between the initial and derived parameters given above.

Estimation of the past and future values of the annual surface and underground runoff (S_{ann} and U_{ann}) needed additional water-balance calculations. For the optimum of Holocene and the predicted period of 2050, the surface runoff was determined by the linear formula of its connections with the annual precipitation total and mean July temperature. The basis of calculations is that, according to the GISS climatic prognosis, the anticipated changes in geophysical parameters will not go beyond the contemporary (for the last 100 years) climate variations, for which the data of instrumental observations are available. Therefore, these periods may be calculated using the contemporary connections expressed by an equation of multiple regression with the high coefficient of correlation R (see above).

The situation for the periods of 2030 and 2050 will be quite different. The state of the atmosphere will probably go beyond its variations in the historical past known by the factual data. New factors will appear, the main of them being the increase of atmospheric humidification along with the temperature growth, which almost was not observed previously [33]. A similar pattern occurred in the optima of the Mikulino (Eemean) interglacial period when the climate was not only warmer but also much more humid than at present [41,42]. In these cases one may use a single-factor connection of surface runoff with atmospheric precipitation by exponential equation (though with the lower coefficient of correlation than in the first case – 0.82):

$$S_{\text{ann}} = \exp\left(2.402 + 0.004 \cdot r_{\text{ann}}\right) \tag{28}$$

Summer reserves of productive moisture in the soil (per 1 mm) correlate well with a complex of three hydrothermal attributes: r_{ann}, S_{ann}, and E_0(see above).

However, the moisture content in soil is still more closely (by the exponential law) connected with the mean July temperature and with other energy parameters derived from it ($\sum t \geq 10^0$, E_0). Thus, the shifts in the state of hydro-edaphotops must be determined by not only rainfall increase or decrease but also the changes in the water balance expenditure (runoff and evapotranspiration) which, in their turn, are determined by the thermal conditions of the warm period.

Reconstruction and prognosis of the primary productivity of natural ecosystems may be estimated by two methods. The first of them is based on the calculations of the past or future values of the annual radiation balance and the index of aridity. With this purpose, we have obtained an empirical relation of the annual radiation balance (by the data of direct actinometrical observations) and the mean July temperature on the territory of the Volga River basin and adjacent regions of the Russian Plain (middle and south taiga, Priladozhye and Prionezhye, as well as the Onega and Northern Dvina basins, the entire steppe and forest-steppe left bank of the Dnepr river, forest-steppe and northern steppe regions of Central Russian Upland and, finally, dry steppe and semi-deserts of the Lower Don and Northern Caucasia). The above relation is a parabola that is linear for most of the territory:

$$R_{\text{ann}} = 12.03 + 0.0214 \cdot t_{\text{July}} + 0.0044 \cdot {t_{\text{July}}}^2; \;\; \text{R} = 0.88 \tag{29}$$

Utilizing this relation it is possible to come to the predicted values of annual radiation balance and, accordingly (with the account of atmospheric humidification), to radiation index of aridity. Then the background values of the primary bio productivity of landscapes are found by empirical nomogram (see Figure 5) for the given calculated epochs and periods.

The calculations showed that even for 2075 the predicted field of R_{ann} and I_{drou} goes significantly beyond the limits of their contemporary combinations on the territory of the Russian Plain. The same could be referred to the optimum of Mikulino interglacial period. Within the Volga River basin and adjoining regions at present there are no combinations of high values of the radiation balance (more than 1900–2000 MJ/m^2) and quite low values of the index of aridity (below 0.7–0.8), at which the productivity of natural vegetation must significantly exceed 14 ton/ha per year. Such hydrothermal conditions are typical of the contemporary humid forest formations of the extreme south of the sub-boreal belt and even the subtropical belt, e.g., Colchis and Lenkoran lowlands, where the productivity of forests exceeds 24 ton/ha (see Figure 5). These data were used for extrapolation prognosis of the primary productivity of natural ecosystems of the Volga River basin for 2075 and 2100 for the regions (mainly west and north-west), where the combinations of predicted R_{ann} and I_{drou} values exceed the limits of the nomogram on Figure 5.

The primary bio productivity can be also calculated directly via the initial hydrothermal parameters (Figure 7). The results of simulation modeling show [43] that under global warming the changes in the structure and productivity of boreal forests and their corresponding role in the global carbon turnover must be directly associated first of all with the increase in the duration of the vegetation period T$_{veg}$. Our data support this assumption. Not only the classes of plant formations but also soil groups have the highest spatial interrelation with the Tveg proper (see Table 1), which in turn is closely related to the July and January temperatures (see above). The primary productivity of natural ecosystems is calculated based on the parameters r_{ann}, t_{July} and T_{veg}, (see above). This dependence is note worthy because it exposes the correlation of the roles of temperature and precipitation in the production of primary organic matter. As is seen, the major limiting factor in the middle area of the Russian Plain (from south taiga to meadow steppe) is the annual rainfall but not the mean July temperature or duration of the vegetation period. Partial dependence of P_{prim} on r_{ann} is very high (R = 0.92) and parabolic (almost directly proportional):

$$P_{\text{prim}} = 0.02585 \cdot r_{\text{ann}} - 0.00000973 \cdot {r_{\text{ann}}}^2 - 2.27 \tag{30}$$

The connection of P_{prim} with t$_{Jul}$ is much weaker (R = 0.82) and expressed by an inverse parabola:

$$P_{\text{pxim}} = 2.001 t_{\text{july}} - 0.07161 {t_{\text{July}}}^2 - 1.92 \tag{31}$$

As a whole, the primary bio productivity decreases from the middle taiga to south steppe, i.e., as the summer temperatures increase and the annual rainfall declines, despite the vegetation

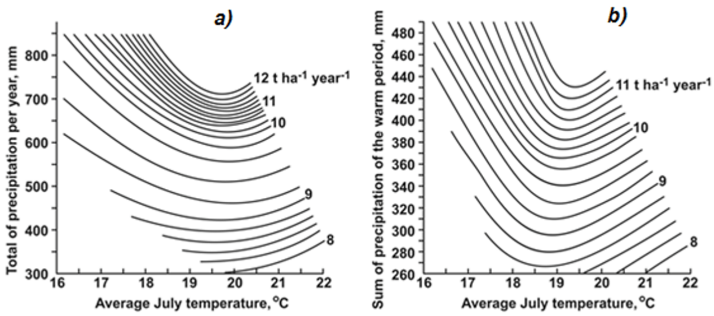


Figure 7 East-European Plain. Dependent of primary bioproductivity from average July temperature and sum of precipitation: per year (a) and of the warm period (b).

period becomes longer: first insignificantly (within the middle and south taiga this connection is "fuzzy") and then more and more abruptly.

One more important pattern should be noted. The chain reaction model shows that the productivity of forest communities is a functional parameter, quite autonomous from their very structure, which has already been empirically proven many times [23, 37]. Autotrophic biogenesis directly depends on the hydrothermal conditions of the surface atmosphere. Annual evaporativity (i.e. mainly the temperature of the growing season) and the atmospheric humidity factor affect P_{prim} 3–4 times more than the structure of the vegetation cover or soil. In the first case, the parameter *C(A;B)* is 0.200–0.240, which corresponds to a correlation coefficient $\geq$ 0.75–0.85), and in the second, it does not exceed 0.05–0.08, i.e. turns out to be below the confidence level (0.07).

6 Regional scenarios of changes in primary bio productivity in the system of background climate fluctuations

To implement such a regional scenario, we turn to the nomograms of dependences of background bio productivity on the main climatic characteristics: the mean July temperature *t*July, annual precipitation *r*ann, and precipitation of the warm period r_{warm} (see Figure 7). Each nomogram has been created based on climatic standards by 120 meteo stations of the Volga River basin and empirical data for primary bio productivity.

The nomograms show quite a dramatic change in the sign of the bonds visible in the range t_{July} = 19–20^0; for annual precipitation, the critical value is $t_{Jul} \approx$ 19.5^0. The increase in summer temperature is accompanied by the decrease in precipitation at $t_{July} <$ 19.5^0 and by its increase at $t_{July} >$ 19.5^0. By crossing the critical temperature threshold, the hydrothermal structure of the annual humidity factor per se changes (see Table 1). It turned out that isolation of the critical radius takes place on the East European subcontinent in the transition zone from the boreal to the sub-boreal belt [18, 21], and in many places, it approaches the Main landscape boundary of the Russian Plain, according to [4].

In this relatively narrow transitional zone, drastic changes occur in the natural ecosystems of the zonal type due to the most important climatic boundary: the F_{hum} crossing 1. The boreal belt differs from the northern (forest-steppe and steppe) part of the sub-boreal belt like migration of substances (mainly abiotic in the first case and biogenic in the second case), the type of background soil formation process (podzolic and soddy, respectively) and, finally, the reserves of organic matter and primary bio productivity [21].

Based on empirical nomograms (see Figure 7) and using the ergodic properties of the climate system, it was possible to obtain model ideas about the changes in productivity with the increase in the mean July temperature *t* with a step ($t_0 \rightarrow t_1$) and the simultaneous change in precipitation *r* (Figure 8). It was taken into account that warming can be accompanied by both increase ($r_0 \rightarrow r_1 \rightarrow r_2 \rightarrow$ ...) and decrease ($r_0 \rightarrow r_{--1} \rightarrow r_{--2} \rightarrow$ ...) in precipitation. Let us consider the model situations of the ratios of considered parameters (Δt, Δr, and ΔPC) separately for each bioclimatic belt, using the examples from the data in Figure 8. We emphasize that these situations relate mainly to the zonal (and sub-zonal) types (and subtypes) of the plant cover, its local representatives being biogeocoenoses of the eluvial (placental) series.

In ***the boreal belt***, with an increase in the mean July temperature (+ $\Delta t = t_1 - t_0$), the following scenarios are possible:

(1) If precipitation remains unchanged (Δr = 0), the primary bio productivity increases,

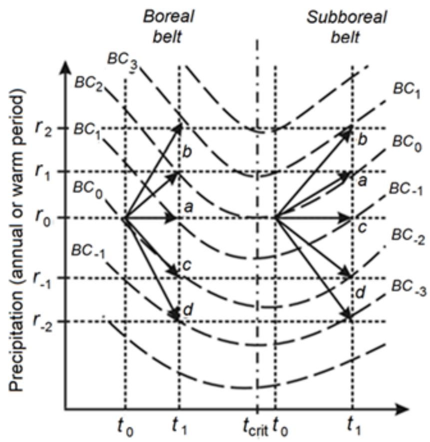


Figure 8 Model representations of the dynamics of primary bioproductivity under various variants of changes in the average July temperature and amount of precipitation (annual or warm period)

although it is relatively low (+ $\Delta(PC) = PC_0 \rightarrow PC_1$); for example, in the range r_{ann} = 700–800 mm, an increase in t_{July} by 1^0 ($17^0 \rightarrow 18^0$) gives an increase in productivity by 600–900 kg/ha; with annual precipitation of 570–630 mm, this increase does not exceed 200–300 kg/ha;

(2) A much greater increase in the productivity of boreal forests will occur during the thermo-humid trend when summer warming is accompanied by a progressive increase in precipitation (+ $\Delta r = r_0 \rightarrow r_1 \rightarrow r_2$; + $\Delta(PC) = PC_0 \rightarrow PC_2 \rightarrow PC_3$);

(3) Bioproductivity can remain at the initial level ($\Delta(BC) = 0$) if precipitation decreases with the increasing temperature (–$\Delta r = r_0 \rightarrow r_{--1}$), and very significantly; the same increase in t_{July} by 1^0 should be compensated by a decrease in annual precipitation from 40–50 to 100–110 mm and precipitation in the warm period to 80 mm;

(4) Under conditions of explicit thermal aridization when warming is accompanied by a noticeable decrease in atmospheric moisture content (–Δr = $r_0 \rightarrow r_{--1}$), productivity will drop significantly (–$\Delta(PC) = PC_0 \rightarrow PC_{--1}$).

The following scenarios are characteristic of ***the sub-boreal belt***:

(1) A relatively minor increase in precipitation (+ Δr = $r_0 \rightarrow r_1$) does not cause any noticeable changes in primary bio productivity ($\Delta(PC) \approx 0$), despite the increase in summer temperature. So, at $\Delta t_{July} = 1^0$ ($20^0 \rightarrow 21^0$), to preserve the initial productivity, it is necessary to increase r_{ann} by 25–50 mm and rtp by 10–20 mm;

(2) Productivity can increase (+ $\Delta(PC) = PC_0 \rightarrow PC_1$) only with a more significant increase in precipitation (+$\Delta r = r_0 \rightarrow r_2$), i.e., under conditions of a significant thermo-humid trend;

(3) The increase in summer temperatures not accompanied by an increase in atmospheric moisture content ($\Delta r \approx 0$) initiates the development of the thermo-aride trend, which causes a decrease in primary bio productivity (–$\Delta(PC) = PC_0 \rightarrow PC_{-1}$); at a constant annual precipitation, on average, for every 1^0 increase in t_{Jul}, there is a decrease in productivity by 200–800 kg/ha;

(4) Further development of the thermo-arid trend caused by a progressive decrease in precipitation (–Δr = $r_0 \rightarrow r_{-1} \rightarrow r_{-2}$) against the background of rising temperatures leads to an even greater decrease in the bio productivity of sub-boreal forests (–$\Delta(PC) = PC_0 \rightarrow PC_{-2} \rightarrow PC_{-3}$).

Thus, boreal and sub-boreal zones, even near the border that separates them, dramatically differ from each other in the main functional parameter of forest ecosystems (primary productivity) in response to background climatic fluctuations. The patterns revealed earlier in the general qualitative analysis [18, 21] is given a definite quantitative interpretation, with disclosure of the detailed mechanisms of ecological relations.

7 Conclusion

The above study has proved ample effectiveness of the methodical techniques of analysis and synthesis used in this work, as well as theoretical and practical significance of empirical generalizations. This allowed us to specify and elaborate the known postulates of the theory of bio-geographical and landscape ecotones.

Summing up, it is necessary to mention the following. This work considered the problems of organization and dynamics of only natural (aboriginal) landscapes in different zonal conditions of the boreal ecotone and touches quite little upon the involvement of regional and local anthropogenic factors in the formation of qualitatively new, natural-anthropogenic geosystems. It was done quite deliberately, because the author aimed at a certain re-conceptualization of one of the fundamental postulates of complex physical geography, the theory of geographical zonality, by the example of boreal ecotone as a mega-system with the most pronounced ecological effects of natural interactions. This research process was directed eventually to the solution of the major problem: the development of a theory and methods of regional landscape-ecological prognosis. Introduction into the models under consideration of the parameters of anthropogenic impacts or attributes of technical-genic transformation of geo(eco)systems, which are generally difficult to compare in the wide range of natural zones of the ecotone, would so much complicate the working data arrays that the empirical models on their basis would have lost their main feature: sufficient comprehension and representativeness at the solution of the problems posed.

The assessment of the anthropogenic impact on natural ecosystems requires rather deep knowledge of natural processes and events which are a substance-energy basis of interaction of man and nature. This very basis has been considered in the present work.

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