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RESEARCH ARTICLE

Predictive Assessments of the Impact of Modern Global Warming on the Landscape-Zonal Conditions of the Volga River Basin

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Abstract: Prognostic landscape-ecological scenarios for the near future of the biosphere have been considered for the first time by taking a large region–the Volga River basin–as an example. The analysis was based on a method of regional landscape-ecological prognosis–developed by the author using discrete mathematics methods. Analytical and cartographic models of future landscape-ecological conditions (for 2050, 2075, and 2100) were obtained. The mechanisms of shifts in the mosaic structure of vegetation, soils, and landscapes have been revealed in the study area under different disturbance scenarios of the climatic system–scenarios anticipated in the foreseeable future (by the end of the 21st century). Forthcoming anthropogenic warming, accompanied by an excessive increase in surface runoff, will occur at the expense of a relative decrease in evapotranspiration, and particularly in groundwater flow. A progressively intensifying thermo-arid bioclimatic trend is predicted, with a general northward shift of zonal boundaries and corresponding changes in the soil water regime and vegetation cover structure. The prognostic models show the convergence of phytocoenoses into new zonal vegetation types.

Keywords: global warming, Volga River basin, water balance, vegetation cover, nature zonality, empirical-statistical modelling, regional landscape-ecological prognoses

1 Introduction

The fundamental problems of ecology and geography are known to include the problem of global changes, which is the core of International Geosphere-Biosphere Program. The latter envisages the development of scenarios of the nearest future of biosphere by means of physical models describing base processes and events. One of the most dynamical natural processes, which used to have a great effect on biosphere evolution in the past and will govern its future state, is global climatic trend determined by the changes in chemical composition of atmosphere resulting in the greenhouse effect [1]. This may lead to a series of large-scale ecological consequences, including reorganization of landscape-zonal structure of vast regions. At present researchers have conducted certain studies on the problem of global- climatic and most common ecological scenarios of expected changes of the environment which are powered by the accumulation of anthropogenic $C0_2$ and other greenhouse gases in the atmosphere [2–5]. To use these results in further scientific and practical research in the field of environmental protection, it is necessary to evaluate the common prognostic landscape-ecological situation for each continental region of the Earth. However, the direct use of the global prognostic parameters for regional levels is impractical and can be in error. Global prognoses sketch the most broad outlines of possible changes of the environment and are often accompanied by schematic maps. Unfortunately the scales of such maps are too small (1:30-40,000,000). Ecological predictions themselves are based for the most part on the palaeo-geographical reconstruction (paleo-analogies) by a very scarce net of points with palynogical dates, so they do not describe the regional and local diversity of ecological situations.

The greater impact appears to be in the adoption of the theoretical (calculated) estimation of global climatic changes derived from the models of general atmospheric circulation [2]. However special systematic difficulties emerge here. The main problem is the transformation of global climatic signals into regional ecological ones on a rather large scale of natural landscape types including sub-regional and local plant societies. Therefore, the response of ecological (climatic) niches of these phytocoenoses to global climatic changes is not clear.

Thus, the problem of regional prognostic conception is quite up-to-date. The author has developed a working version of this conception by the example of main catchment area of the Volga River basin. This version considers prognostic landscape-ecological scenarios of the nearest future of the region as a certain system of global changes in the environment. Schematic maps of the shifts of landscape-zonal systems were plotted for the given scenarios of disturbing climatic effects, which are anticipated before the end of the 21st century.

The present report is one of the experiments of the regional landscape-ecological prognosis at a comparatively large scale (1:2,500,000). The analysis includes zonal spaces of the East-European (Russian) Plain: middle and south taiga, mixed forest, broadleaf forest and forest-steppe (together with north steppe). The research region is disposed in coordinates 52–56 ^{0}N and 36–56 $^\circ$E.

Strategy of the landscape-ecological prognosis was as follows: first to carry out an identification of zonal types and regional kinds of landscape units to certain values of contemporary climatic conditions, and then to make an estimate of the most probable transformation of revealed ecological niches of vegetation and landscapes according of expected climatic changes for the given prognostic dates. The author has suggested an ambiguous character of the transformation of geo(eco-)systems at a fixed value of the geophysical trend when a new state can share a number of traits of not one but several states which are known at present instants of time.

In essence, a landscape-ecological prognosis for the nearest several decades (to 100 years) is functional rather than structural. Characteristic (typical) times of metabolic parameters are much smaller than those of morphological parameters of ecosystems [1]. Changes in the rates of organic matter reproduction and decomposition occur within the period ranging from a few months to three to five years [6–8], which is commensurate to the time of general shift in the climatic system itself. Thus, functional relaxation as the primary response of ecosystems to an external factor is a priority object of landscape ecological prediction. The main prediction based on ecological estimation of the forthcoming global climate warming is expected to be functional rather than structural-morphological.

The supposed functional-structural shifts in geo(eco)systems can be determined by climate changes (in this case, anthropogenic changes), with a period of fluctuations of 50 years and more, characterize not the future natural complexes per se but rather the landscape-ecological conditions and, accordingly, the limit of ecological equilibrium, which real biogeosystems will tend to in their variations. The time of reaching this equilibrium calculated in the number of steps τ(s) or in the number of years τ(y) relates only to the functional relaxation but not to the full period of structural transformation. The latter will be determined not only by the intensity of the external effect but also by the characteristic times of different natural attributes, according to [9]. For forest landscape, as is known, the prediction step not exceeding the lifetime of one generation of forest stands makes it possible to determine potential forest growth conditions.

2 Starting Materials

According to Sukachev [10], the main representatives of natural zones and subzones are primary plant formations, the classification scheme of which for the territory of the East-European Plain is given in Table 1. According to the rules of classical phytocoenology [11], the phytocoenological unity identified here refers to the classes (and sub-classes) of plant formations that are regional variants (for example, Eastern European or Kama-Pechersk) of the types and subtypes of vegetation (middle taiga, sub-taiga, etc.). The Volga River basin accounts for 16 groups of indigenous plant associations.

The fundamental concepts of global ecology are based on the close relationship between natural zonality and the heat-to-moisture ratio within the same geographical belt [12, 13]. The known Vysotsky Ivanov's *annual atmospheric humidity factor* F_{hum} is most widely used in the Russian geographical literature. This coefficient is a ratio of total annual precipitation r_{year} to annual evaporativity E_0 (potential evapotranspiration):

$$\mathrm{F_{hum}} = \mathrm{r_{year}}/\mathrm{E_0} \tag{1}$$

Parameters E_0 and F_{hum} are formed mainly by the mean July temperature (t_{July}). For the territory of the Russian (East European) Plain, we obtained the following relationships, with high correlation (R) and determination (R^2) factors:

$$\mathrm{E_0} = 1384 - 161.6 \times \mathrm{t_{July}} + 6.245 \times \mathrm{t_{July}}^2;\ \mathrm{R} = 0.93;\ \mathrm{R}^2 = 0.87 \tag{2}$$

$$\mathrm{F_{hum}} = 12.09 - 0.9095 \times \mathrm{t_{July}} + 0.01744 \times \mathrm{t_{July}}^2;\ \mathrm{R} = 0.94; \mathrm{R}^2 = 0.88 \tag{3}$$

Climatic niches of vegetation form a single continued series by this factor, without any marked leaps and with continuously changing taxonomic norms of F_{hum}. Such series points to a sequence of anticipated phytocoenological transitions at this or that climatic trend. For example, at a F_{hum} decrease from 1.85–1.65 to 1.23–1.12, the fir-woods of middle and south taiga of the Upper Volga must transform into broadleaf dark-coniferous and/or pine formations, and then the latter – into the more continental dark-coniferous subtaiga of the lower Kama river and into broad-leaved and pine forests.

Assessing the present and future values of the water balance components requires additional calculations. First of all, this concerns river flow. According to climate forecasts by GISS model, initial changes in geophysical parameters should not go beyond the limits of climate fluctuations over the last 100 years, for which instrumental observation data are available. Therefore, in modern climatic conditions and in the coming decades (to 2050), the amount of annual surface river flow (S_{ann}) depends on both the annual amount of precipitation (r_{ann}) and average July temperature:

$$\mathrm{S_{ann}} = 0.1028 \times \mathrm{r_{ann}} - 37.724 \times \mathrm{t_{July}} + 794;\ \mathrm{R} = 0.90 \tag{4}$$

Table 1 The classification scheme of primary plant formations of the natural zones of the East-European (Russian) Plain

Plant formations, by Houghton et al. [3]			Groups of plant associations	
Zonal types and classes	Regional versions	Sub-zonal sub-types	Brief characteristics	Number and symbol
Dark conifer and broadleaf– dark conifer forests (secondary aspen –birch)	East European (Upper Volga region)	Middle taiga	Spruce green mosses with smallshrubs	1
		South taiga	Spruce smallshrub-grass	2
		Sub-taiga	Broadleaf-spruce complex nem orose-herbal	3
	Kama – Pechora – West Ural region	Middle and south taiga	Fir-spruce and spruce-fir grass smallshrub, with green mosses, and grass	4
		Sub-taiga	Fir-spruce complex nemorose-herbal	5
			Broadleaf–fir–spruce nemorose–herbal	6
Pine and broadleaf–pine forests (secondary aspen –birch)	East European (Upper Volga Region)	Middle and south taiga	Pine, with spruce, green mosses with small-shrubs	7
		Sub-taiga	Pine (with oak in undergrowth) smallshrub-grass	8
			Broadleaf-pine and pine com plex, with spruce	9
		Forest-steppe and steppe	Pine and broadleaf-pine, with steppe undergrowth, and herbs-cereals	10
Broadleaf forest	East European	Northern forest-steppe	Lime-oak and oak	11a
			Lime with admixture of other broadleaf kinds	11b
Typical and southern forest-steppe	of the Pontic type	Typical forest-steppe	Meadow steppes with combina tion of oak forests	12
		Southern forest-steppe	Rich herb-sheep's fescue-feather grass steppes, with oak copses	13
Northern steppe	of the Trans-Volga type	Northern steppe	Rich herb-sheep's fescue-feather grass steppes	14
Southern steppe	of the Trans-Volga type	Southern steppe	Sheep's fescue-feather grass steppes	15
Semi-desert	of the Trans-Volga type	Semy-desert	Fescue-feather grass steppes in a complex with wormwood on salt licks	16

For periods beyond 2050. the situation will be significantly different. The state of the atmosphere will probably go beyond the fluctuations known from actual data in the historical past. New factors will arise, and the main one is an increase in atmospheric humidity with rising temperatures, which was almost never observed before. Therefore, for a long-term forecast (2075, 2100, ...) it is advisable to use a one-factor relationship between surface runoff and precipitation according to the exponential equation:

$$\mathrm{S_ann} = \exp(2.402 + 0.004 \times \mathrm{r_{ann}});\ \mathrm{R} = 0.82. \tag{5}$$

Summer reserves of productive moisture (in mm) in soil layers of 20, 50 and 100 cm correlate well with a complex of three hydrothermal characteristics:

$$(\mathrm{W} - 20) = 0.0257 \times \mathrm{r_{ann}} + 0.0676 \times \mathrm{S_{ann}} - 0.0136 \times \mathrm{E_0} + 0.8;\ \mathrm{R} = 0.88; \tag{6}$$

$$(\mathrm{W} - 50) = 0.0631 \times \mathrm{r_{ann}} + 0.1746 \times \mathrm{S_{ann}} - 0.0231 \times \mathrm{E_0} + 7.6;\ \mathrm{R} = 0.89; \tag{7}$$

$$(\mathrm{W} - 100) = 0.0964 \times \mathrm{r_{ann}} + 0.3216 \times \mathrm{S_{ann}} - 0.0802 \times \mathrm{E_0} + 33.5;\ \mathrm{R} = 0.86. \tag{8}$$

Calculations are based on the fact that, according to the GISS climate forecast, expected changes in geophysical parameters will not go beyond the limits of modern (over the last 100 years) climate fluctuations for which instrumental observation data are available.

As a base period, we have taken the 100-year interval (1881–1980) of instrumental observations of the hydro-meteorological network with the results published as multiyear climate norms. This interval covers the entire so-called industrial period. During this period, the European territory of Russia passed through the five largest climatic cycles, each about 15 years [14]. The upper limit of fluctuations of 11-year moving averages, which fell on approximately 1985, was taken as the beginning of prognostic period characterizing the modern global warming. Starting with this time, the annual temperature progressively increased during the 80–90 s of the 20^{th} century, leaving the previous extreme points of the base period far behind.

The hydrothermal trends for the period up to 2100 have been taken from one of moderate global coupled atmosphere ocean general circulation models (AOGCMs) – GISS (Goddard Institute of Space Search, USA). This model predicts the relatively temperate global warming [4], which meets the objectives set by the Paris (2015) Agreement on Climate Change. It is one of the most preferable general circulation models, according to the results of testing of statistical significance of the data obtained and simulation of the state of contemporary climate, including its seasonal characteristics [15]. It has been successfully used in a number of prognostic-ecological researches [14, 16, 17]. Initial global model GISS-1988 has been transformed for regional level (territory of Russian Plain) in model GISS-1993 by G.V. Menzhulin and S.P Savvateev according to our request. Transformed model GISS-93 has turned out to be more realistic as compared with the initial model GISS-88 [18].

Primary GISS climatic scenario had been based on the supposition that the doubling of concentration CO_2 in atmosphere as compared with "preindustrial period" (1886–1905) will be reach to year 2050 [19]. More late investigations make to move away this date to the end of 21^{st} century [7, 20]. Proceed from that we will move the dates of GISS scenarios by next manner: 2010→ 2050, 2030→ 2075, 2050→ 2100.

The GISS model forecasts for our region the rise of average January and July temperature 0.5–1.2 °C, 1.5–3.5 °C and 2.5–5.5 °C by years 2050, 2075 and 2100 accordingly. By 2050 amount of precipitation will run to 50–100 mm, in the following 25 years it will increase two-fold, and by 2100 it will grow by 40% more. On that evidence we have compiled maps of present-day landscape-geophysical conditions [21].

Although the rise of summer and winter temperature will be accompanied by a certain increase in precipitation, particularly during the warm season, however the increment of precipitation will be insignificant and it will not be able to neutralize the temperature increase. Therefore the atmospheric humidity factors F_{hum} and summer stored soil moisture will start to decrease almost everywhere and quite significantly (Table 2). Besides, *the progressive summer aridization of soil* will begin: the common event for the moderate belt of continents [35].

3 Methods

All forecast landscape-zonal constructions (both analytical and cartographic) are based on a fairly close regional connection of plant communities with the parameter F_{hum} (Table 3). For example, with a decrease in F_{hum} from 1.85–1.65 to 1.23–1.12, the middle and southern taiga

Table 2 Taxonomical standards of atmospheric humidity factor and summer soil moisture content on the Volga River basin and their forecasted changes, according to GISS-93 model

Groups of Associations	Atmospheric Humidity Factor (F_{hum})			Annual Surface Flow (S_{ann}), mm			July Stored Soil Moisture in Layer 1 m *(W-100)*, mm		
	Base period	2050	2100	Base Period	2050	2100	Base period	2050	2100
1	1.80	–0.14	–0.24	213	40	79	181	–39	–125
2	1.42	–0.16	0.07	203	55	80	134	–14	–65
3	1.73	–0.13	–0.21	187	70	122	167	–52	–105
4	1.47	–0.02	–0.08	148	61	89	130	–23	–70
5	1.54	–0.01	–0.18	148	89	126	129	–14	73
6	1.23	0.06	–0.03	157	52	91	121	1	70
7	1.07	0.04	–0.04	123	49	73	103	–32	60
8	1.21	–0.09	–0.13	100	61	77	95	–31	–88
9	1.12	–0.02	–0.15	109	27	51	78	–22	–46
10	1.07	–0.10	–0.19	64	28	36	103	–34	–67
11	0.94	–0.02	–0.10	104	32	45	71	–21	–45
12	0.80	0.05	–0.08	82	28	41	64	–21	–44
13	0.90	–0.06	–0.27	64	45	33	62	–25	–44
14	0.72	–0.02	–0.26	51	37	26	46	–19	–32
15	0.62	0.06	–0.03	50	26	32	38	–4	–20
16	0.57	–0.11	–0.26	31	21	27	28	–5	–18

Note: Conventional meanings of plant association groups see in the Table 1.

fir-spruce forests of the Upper Volga should transform into broadleaf/dark-coniferous or pine associations, and the latter – into a more continental dark-coniferous sub-taiga of the Kama River basin, as well as into broadleaf-pine forests.

Summer moisture content in soil also correlates well with annual atmospheric humidify factor, determining the latitude-zonal character of its distribution both at present, in the past and in the future. For forest ecosystems of the Volga River basin, the connections between the July productive stored soil moisture in soil layer 0–100 cm (*W-100*) deep are with F_{hum} is follow:

$$(W-100) = exp[3.225 + 1.134F_{hum}(1)];\ R = 0.88;\ R^2 = 0.77. \quad (9)$$

The prognosis-preceding stage in the analysis used a information theory methods [5,22]. By means of binary subordination an important methodical problem were decided the revealing of ecological niches of one or other state of the studied phenomenon X (landscape kinds) in a set of states of the given geophysical factor Y. On all states a, of phenomenon X with their conditional probabilities p(x/y) partial association coefficients were calculated: L(x/yj) ≈

p(x/yj)/P(x), where P(x) is an a priori probability of class graduation x, of phenomenon. It is agreed that by coefficient L(x/yj) > 1 the association is significant. The matrix of partial association coefficients describes a system of ecological niches of landscape kinds as defined ”zones of consumption” in space of changes of the given geophysical parameters [1]. This concept refers to the biotic landscape components, in this instance to the vegetation cover.

Table 3 Ecological optimums (×) and “blurred” parts of ecological niches (•) of plant formation groups in the space of the values of the Vysotsky-Ivanov’s humidity factor (Fhum) on the territory of East-European (Russian) Plain

Gradation of humidity factor	Formation group associations (see Table 1)															
																
0.50-0.61														•	×	×
0.61-0.73													•	×	×	•
0.73-0.82											•	•	×	×	•	
0.82-0.96										•	×	×	•	•		
0.96-1.04								•	×	•	×	•	•			
1.04-1.12						•	•	×	×	×	•					
1.12-1.23						×	×	•	•	•						
1.23-1.33			•	•	•	•	×			•						
1.33-1.45			×	×	×		•									
1.45-1.55		•	•	×	•	•										
1.55-1.65	•	•	×	•	•											
1.65-1.75	•	×	•	•												
1.75-1.85	•	×			×											
1.85-2.00	×	•			•											
Taxonomic norm of F_{hum}	1.80	1.73	1.47	1.42	1.54	1.23	1.21	1.12	1.07	1.07	0.94	0.90	0.80	0.72	0.62	0.57

Note: The sign “×” denotes the optimum of dominance of the equivalence classes; “•” is the “blurred” part of this niche.

It is taken that each value $L(x/y_j)$ is a certain equivalent of probability of the landscape kind i by the given graduation / of a geophysical parameter. The probability is the higher, the greater the coefficient. Each ecological niche can accordingly be represented by some descriptive multitude in the form of the row vector. Volumes of $L(x/y_j)$ which are considered here as ”weighting” coefficients will be components of such vector.

Each row vector specifies the state of the corresponding landscape kind in relation to one or other geophysical attribute, that is $X \leftrightarrow$ $(Li, L_2 \quad \ldots \; L_n)$. For example, in relation to the average July temperature one landscape kind has niche $A\leftrightarrow$ (4.47 2.97 2.20 3.87 3.81 0.88 0 0), and other kind - the niche $B \leftrightarrow$ *(0* 0 1.06 0.38 2.07 5.10 0.95 0). On combining vectors by components and excluding from the following treatment all $L(x/y_j) < 1$ we have a mutual intersection of these two landscape kinds on only two (the third and fifth) graduations of temperature (it is equal: 1.06 + 2.07 = 3.13).

On the basis of obtained bank of ecological niches the probabilities of landscape transitions for the given prognostic dates were estimated. For this purpose the measures of

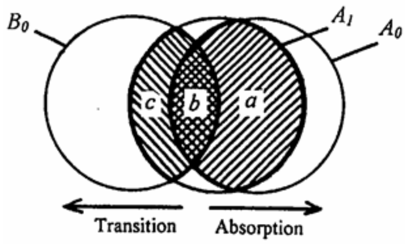


Figure 1 Venn’s diagram, illustrating the mechanism of probability estimation of landscape-ecological transitions (explanation in the text)

inclusion for descriptive multitudes reflecting contemporary and forecasting partial climatic niches of the landscape kinds under review are calculated (Figure 1). It is taken that A_0 and A_1, are respectively an initial (contemporary) and a final (future) values of the row vector of the ecological niche of landscape A which must be absorbed by another landscape B if its niches will intersect each other in the final state more than in the initial that. The landscape transition proceeds in the direction $A\leftrightarrow$ B, and the absorption proceeds in the opposite direction $B\leftrightarrow$ A. The shaded area a+b+c on the diagrams reflects the summary value of the transformation of landscape A which can be expressed in terms of the following measure of inclusion by Leemans [23] and Odeh [24]:

$$a + b = A_0 \cap A_1; \quad b = A_0 \cap B_0; \quad b + c = A_1 \cap B_0. \tag{10}$$

where "∩" is the sign of intersection (logical product) of two sets. The elements of the intersection "zone" belong to two sets simultaneously.The elements of the intersection "zone" belong to two sets simultaneously. In each pair of landscape kinds *A* and *B* two parameters of transformation are counted: *K(*A_0*—>A,)* - the stabilization measure P_u of kind *A* and *K(*A_0*-ˆBJ* - the measure $P,_t$ of its absorption by kind *B*. These parameters are expressed by the following measures of inclusion:

$$K\,(A_0 \rightarrow A_1) = \frac{A_0 \cap A_1}{A_0} \tag{11}$$

Since the operations are performed with descriptive sets, the operating formulas have the next shape:

$$K(A_0 \rightarrow A_1) = \frac{\sum \min\left[L_i(A_0), L_j(A_1)\right]}{\sum L_i(A_0)} \tag{12}$$

$$K(A_0 \rightarrow B_0) = \frac{\sum \min\left[L_j(A_1), L_k(B_0)\right] - \sum \min\left[L_i(A_0), L_k(B_0)\right]}{\sum L_i(A_0)} \tag{13}$$

Here *i*, *j* and *k* are the order numbers of partial association coefficients in the row vectors describing ecological niches A_0, A_1 and B_0, respectively.

By analogy, we calculate the values of transitions $K(A_0 \rightarrow C_0)$, $K(A_0 \rightarrow D_0)$, etc. For the following state, we have $K(B_0 \rightarrow B_1)$, $K(B_0 \rightarrow C_0)$, $K(B_0 \rightarrow D_0)$, etc. For the next stage of prediction, its measures of transition are calculated: $K(A_0 \rightarrow A_2)$, $K(A_0 \rightarrow B_0)$, $K(A_0 \rightarrow D_0)$, . . .; $K(B_0 \rightarrow B_2)$, $K(B_0 \rightarrow C_0)$, $K(B_0 \rightarrow D_0)$, ...

Thus, a specific quadratic matrix of probabilities of stabilization of each object (diagonal elements of the matrix, P_{ii}) and its transitions into other objects (P_{ij}) is obtained for each prediction period. Here, the zero and negative values of probabilities are possible. The former indicates the absence of transitions and the latter show intensification of the contrast between the functional states of objects (at $A_1 \cap B_0 < A_0 \cap B_0$). Further operations are executed with the transition probability matrices. All negative transitions are provisionally replaced by zeros.

Account was to be taken of simultaneous changes of all four cited climatic factors: the average January and July temperature and precipitation of cold and warm periods. Therefore earch factor had its "weighting" coefficient. In consiquence we have obtained the weighted-average matrices of probabilities of stabilization of each landscap kind and its transition to all other kinds.

The second stage of the analysis was the following procedure: potential rates $h_{i\}}$ of transitions and average times t_{tJ} of the full or partial absorption of the niche of one landscape kind by the niche of other kinds were calculated. For this purpose the mathematical apparatus of Markov's chains theories were used [25]. In first turn we have obtained the total rates of transition *M,* from the given state in one step, that is to say in time interval *d* = 1. In general:

$$M_i = -lnP_{ii}/d.andbyd = 1.\; M_i = -lnP_{ii} \tag{14}$$

By $M_i = 1$, relative partial rates of transitions m_{ij} from i-state to j-state are found by the correlation: $m_{ij} = P_j/P_i$. The expected total time of residence of the system in state L, that is to say up to the moment when it will give way to all other states, is alike: $t(P_i) = 1/M_i$. By multiplying of value $t(P_i)$ into the time equivalent of the first step (20 years in our case) we obtain the expected absorption time (in years) which makes conceptually the final time of full transformation of the given landscape climatic niche. Next it is essential to calculate h_{ij}, which is an absolute partial rate of transition of *i*-landscape niche to *j*-niche (as a conditional probability). This rate is equal: $h_{ij} = m_{ij} \times Mi$.

Values h_{ij} are calculated on all lines of matrix P_{ij} (except its diagonal elements). The relation h_{ij}/M_i, show us that part of the total one-step reduction of the niche property of /-landscape kind (for example, area or the part of any other attribute of transformation) which accounts for the transgression of y-kind niche. It is thereafter an easy matter to calculate what part of properties of the given landscape kind will be absorbed by other kinds at time intervals (steps), those are 20, 40 and 60 years.

On matrices of parametr h_{ij}, the prognosis landscape-ecological maps were compiled. They show areas of future equilibrium states of vegetational cover which correspond to equifinal stages of the exo-dynamic phytocoenosis successions. However the terms of the onset of these states remain unknown, and its definition is an independent geobotanic problem. The prognosis maps present two dynamic characteristics simultaneously: 1) prevailing tendency of transitions of the niche of the given landscape kind from "its" natural zone (sub-zone) into the landscape niche of other zone; 2) common degree (or rate) of inter-zonal transformation of the climatic niche of the given kind. Both mentioned above characteristics are well represented in the legend to the prognosis maps of landscape-ecological conditions [26].

For predictive landscape-zonal mapping, basic values of F_{hum} were taken (with an interval of 25 km) at the boundaries of natural zones and sub-zones and processed statistically. Each boundary included 95 to 280 points. For most boundaries, the distribution of F_{hum} turned out very distant from the norm, with marked negative excesses, therefore we had to divide each of the excerpts into two or three sub-excerpts according to the longitude-sector division of the zonal or sub-zonal boundary. The coefficient of variation of parameter F_{hum}in each of the combinations obtained did not exceed 4–6%, and only for the boundaries of forest-steppe and steppe zones it was 10–11%. As a whole, this is an evidence of high significance of the obtained spatial connections of zonal and sub-zonal boundaries with the index of annual warmth to humidity ratio. These connections were further used for prognostic mapping of the system of natural zones of the region, on the basis of the corresponding maps of annual atmospheric humidify factor.

In contrast to rather schematic data on the global system of landscape-geophysical connections [27], as well as analogous scanty information on the Russian Plain [28], the stricter and more statistically substantiated regularities of the distribution of coefficient of humidification over natural zones (subzones) have been obtained for the territory of the Volga River basin, with two longitude-sector versions (Table 4). Extreme values of each F_{hum} interval fall on the southern and northern boundaries of the corresponding natural zone or sub-zone. Values of F_{hum} parameter for more southern boundaries of given region was next, according [18]: between north and middle steppe – 0.60; between middle and south steppe – 0,50; between south steppe and semi-desert – 0.32.

Table 4 Comparison of zonal-regional atmospheric humidity factors for territory of Volga River basin with the same coefficients which reflect the natural zonality of Russian Plain and the planetary system of zonality as well

Nature zones (sub-zones)	World system of nature zones [30]*⁾	Russian Plain [31]	Volga River basin and its encirclement	
			West sector	East sector
Middle taiga	1.87–2.00	1.07–1.76	> 1.88	> 1.62
South taiga		1.33–1.69	1.63–1.88	1.35–1.62
	1.52–1.61			
Mixed forest		0.78–1.46	1.22–1.63	1.00–1.35
	1.20–1.24			
Broadleaf forests		1.08–1.18	1.09–1.22	0.97–1.00
	0.99–1.03			
Typical and south forest-steppe		0.67–0.98	0.76–1.09	0.76–0.97
	0.73-0.74			
North steppe		0.51-0.80	0.70-0.90	0.60-0.76

Note: *⁾ Data are showed for the boundaries between nature zones and sub-zones.

Quite significant were the intra-zonal longitude-sector changes in the warmth to humidity ratios determined by climate continentality. The greater continentality corresponded to the lower F_{hum} value, which conformed to the boundary conditions of a given natural zone (subzone). Even within the boundaries of the Russian Plain, one and the same zonal subdivision in the eastern, more continental sector is distinguished by higher aridity, and this longitudinal shift of relative humidity is comparable to the shift of zonal boundaries southwards for a whole sub-zone.

4 Results and Discussion

4.1 Changes in the water balance and summer stored soil moisture

We have worked out components of water balance of territories relating to river systems of the Upper and Middle Volga for 2050, 2075 and 2100 (Table 5). Empirical regional associations with the annual precipitation total in terms of linear regression equations with correlation coefficients 0.61–0.83 were used for the prognosis of surface river flow. The greatest increase in the water balance is suggested for surface runoff (25–40% to 70–85% in 2100). This will be accounted for by the rise of precipitation amount (22%) as well as by the relative reduction of the share of the groundwater flow in the water balance of the territory (from 28% by the year 1990 to 19% by the year 2100) by its common absolute increase of 15–20% in all nature zones except for north steppe and forest-steppe.

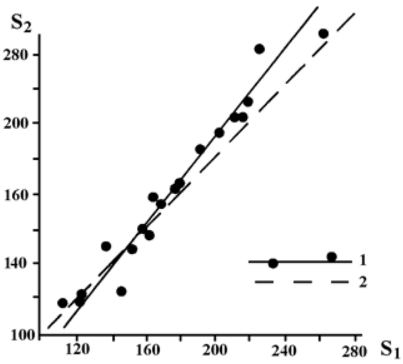
Table 5 Volume increase of water balance components of Volga River Basin for prognostic year 2100 (in % by 1990), according to GISS model

Nature zone (sub-zone)	Precipitation (r_{ann})	Evaporation (E_0)	Surface river flow (S_{ann})	Groundwater flow (U_{ann})
Middle taiga	20	10	55	17
South taiga	28	4	70	13
Mixed forest	25	12	69	23
Broadleaf forest	30	19	42	15
Forest-steppe	25	6	76	0
North steppe	4	18	35	0
Whole region	25	11	61	15

Even at present it markedly increases in the Volga catchment basin. The comparison of runoff layer values calculated for the period of observations up to 1980 and 1990, separately, shows that these values increased for 7% on the average, at the extension of a series of observations for 10 years (Figure 2). The maximal growth of runoff layer will occur in the western sector of south taiga and mixed forests, the medium growth – in the subzone of broad-leaved forests, and the minimal growth – in southern forest-steppe and northern steppe. Numerical experiments with global models also give the increase of the flow in the continental regions lying north of the 50th parallel [29].

The groundwater flow and total evaporation will increase to a much lesser extent. According GISS model, in 2050, 2075 and 2100, their values (as compared with 1990) over the region on the average will increase as $5 \rightarrow 9 \rightarrow 15\%$ and $4 \rightarrow 6 \rightarrow 11\%$, respectively, and the surface runoff in forest-steppe and northern steppe actually will not increase. At the same time, the ratio of subsurface to surface runoff for the whole period will decrease from 0.28 to 0.19 on the average. In broadleaf forests and north steppe the total evaporation will equally increase (on the average, by 19%), what will correlate with the

increase by 13% of common humidification of these territories. At the sacrifice of the rise of precipitation amount the common humidification will increase in the zones of mixed forests and forest-steppe.



1 – actually linear correlation;
2 – hypothetical straight line for condition what $S_1 = S_2$.

Figure 2 Correlation of values of annual complete flow (mm) for the observation periods before 1980 (S_1) and before 1990 (S_2) on the territory of headwater of Volga River basin

Thus, there will occur not a simple and unambiguous shift of all water balance components towards the increase, but reorganization of the very structure of the balance, i.e., of the ratio of its expenditure components – runoff and evaporation. This reorganization will consist in a disproportionately great increase of the share of surface river runoff due to a relative decrease of evaporation and subsurface flow. At the same time, the total expenditure of atmospheric moisture for the surface and subsurface runoff will increase much more than the expenditure for evaporation, which will cause general increase of runoff coefficient. Such a change in the water balance structure will indicate a decrease in the extent of closure of the water cycle, which in turn, according to [26], should be considered as a significant cause of the decrease in tolerance of geo(eco-)systems for outer influence and as factor of the weakening of their resistance to external, including anthropogenic, impacts.

Almost all forecast-climate models of the AOGCMs family of atmospheric general circulation assume a general summer drying of soil in the south of the temperate zone of continents during global warming – due to a sharp increase in evapotranspiration [7, 30]. GISS model transformed to the regional level are no exception. Over the whole territory of the basin, quite a significant decrease of soil moisture reserves in the middle of vegetation period is also predicted (see Table 2). It will be determined by the forestalling increase of summer temperatures as compared with the increase of precipitation of the warm season, which will reduce the atmospheric humidify factor. Significant decrease of productive soil moisture resource in the middle of vegetation period will be caused by quite a number of reasons: reduction of fore-spring snow resource, the earlier disappearance of snow cover and, finally, which is most important, increased evapotranspiration at a falling F_{hum}.

So, in Podmoskovye (the near-Moscow territory) already in 2050 the level of moisture content in soil is expected to fall for 17%, which will bring it nearer to the minimum in the spectrum of modern fluctuations of humidity (22% from the average for the period of observations 1965–1984 [11]. In 2075, the decrease in the many-year norm of moisture reserves will be 1.5-fold less than this minimum, and in 20 more years the decrease will be 2.5-fold. Thus, already at the second prognostic stage, the many-year reserves of productive moisture in soil will go beyond the lower level of their contemporary year-to-year variability.

By the middle of the 21^{st} century, the July moisture reserves in a 1-m soil layer of agro-phytocoenoses in the sub-zones of middle and south taiga will decrease from 130–180 mm to 50–70 mm (see Table 2), which will be 5–7 times lower than their minimal moisture capacity (at present, this ratio does not exceed 1.5–1.7). The soil moisture reserves in the zone of mixed forests will fall practically to the same level. By deficit of summer moisture content, sod-podzol soils will approach to the contemporary state of not only gray forest soils of broad-leaved forests, but also leached and podzolic chernozems of typical forest-steppe. From its part, aridization of gray forest soils will bring them to the state of contemporary meadow chernozems of southern forest-steppe, as well as typical and common chernozems of northern steppe ((*W-100*) = 30–40 mm). The latter, in their turn, will be aridized towards semidesert chestnut soils.

The predicted thermo-arid bioclimatic trend will inevitably aggravate the problem of maintenance and reproduction of forest and water reserves, as well as crop growing in the forest-steppe and steppe zones of the Russian Plain. Interpretation of ecological prognosis on the basis of the known effects of soil moisture content in vegetation period on the state of natural plants and agro-phytocenoses [8, 31] leads to the following conclusions:

(1) In 2050, natural reproduction of forest species will have become difficult not only in northern steppe, but also in typical and southern forest-steppe. By 2075, such situation will have occurred also in the subzone of broad-leaved forests. At a decrease of July moisture reserves in 1-m soil layer to 25–30 mm, the viability of mature stands will abruptly decrease, dooming them to dry out. In 20 more years, the critical conditions of reforestation will also spread over the mixed-forest zone.

(2) Agro-climatic conditions will be as unfavorable. In 2050, natural 20–30% decrease in the yield of cereals should be anticipated in forest-steppe zone at summer (*W-100*) = 50–70 mm. In 2075–2100 , the zone of mixed forests will be in the same conditions, while further decrease of soil moisture reserves in the forest-steppe to a level of 20–35 mm will cause a yield loss of 40–50%.

It is absolutely evident that global warming already in the nearest decades will cause the demand of additional and quite considerable energy expenses for irrigation in order to maintain the necessary areas of forest stands and crop yields in the Middle Belt of the Russian Plain, where the main cereal belt of European Russia.

4.2 Prognosis Evaluates of State of Regional Bioclimatic System

Integral measures of the greatest possible mutual transformation of climatic niches between different natural zones (sub-zones) give the most common idea about the regional pattern of the expected landscape-ecological tendency. To obtain these measures the generalization has been performed on each zone of probabilities of landscape transitions based on a relative area which is occupied by each landscape kind. Based on the weighted-average volumes over the territory of the zone of transition probabilities the summary (M_i) and partial (*Mij*) measures of transformation rates of zonal geospaces were calculated then for all three prognostic dates (Table 6).

Table 6 Summary values of transformation rates M_i of geospaces (total time (year) of the complete transition of contemporary zonal-climatic area to other areas) for prescribed prognostic dates (with growing result)

Natural zone (sub-zone)	Date (step) of climatic prognosis		
	2050	2075	2100
Middle taiga	0.598 (33)	0.884 (70)	0.967 (111)
South taiga	0.585 (34)	0.863 (72)	1.070 (97)
Mixed forests	0.646 (31)	0.910 (76)	1.152 ((83)
Broadleaf forests	0.664 (30)	0.911 (81)	1.121 (95)
Forest-steppe, north steppe	0.333 (60)	0.421 (228)	0.569 (152)

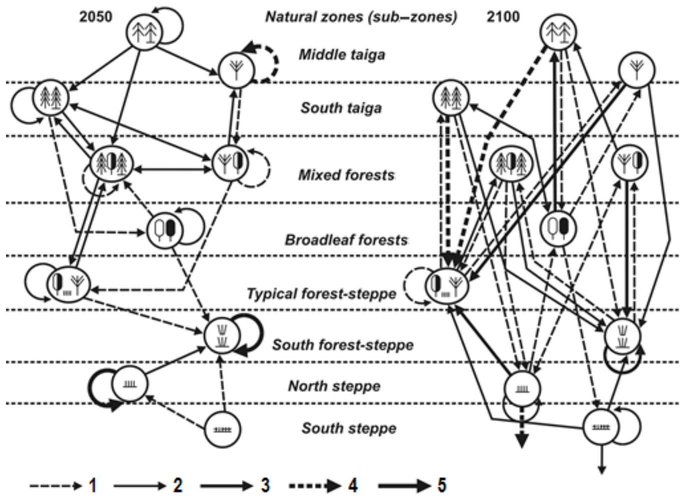


Figure 3 Vector graphs of the probabilities of functional transitions between the plant association groups of the headwater of Volga River basin (see Table 1) on the prognostic periods up to years 2050 and 2100, according GISS-1993 model. Probabilities of inter-association transitions: 1 – 0.20 and less; 2 – 0.21–0.30; 3 – 0.31–0.40; 4 – 0.41–0.50; 5 – 0.51–0.60.

Up to the end of the 21st century, *the thermo-arid climatic trend* will develop on the territory of the Volga River basin and its surroundings (Figure 3). This is evidenced by the negative values of changes in the atmospheric humidity factor dominating at all stages of the forecast period, as well as July reserves of productive moisture in soil (see Table 2). The anticipated global anthropogenic warming will cause *general aridization of the regional bioclimatic system*, and this aridization will become still deeper and more total with time. Ultimately, on the place of the sub-zone

of broad-leaved forests and southern band of the sub-taiga zone in Middle Volga Region will be taken by developing *coniferous (pine) forest-steppe as a new (for this region) zonal ecotone of direct contact between boreal and steppe plant formations*, with a mosaic complex of light-coniferous and oak/small-leaved park forests, meadows, and steppes. Obviously, this will be one of the variants of the general process of *"savannization"* of the sub-zone of broadleaf and fixed forests of the Russian Plain under global warming.

The rise of the amount of atmospheric precipitation and the concurrent increase of temperatures should extend significantly an ecological space in each natural zone, build up the multitude of new climatic niches and enlarge accordingly a territorial diversity of zonal and edaphic phytocoenosis structures and lastly initiate new landscape boundaries, this is the universal reinforcing of the territory ecotonization. The difference in productivity of zonal vegetation cover, especially between south taiga and mixed forest, on the one hand, and forest-steppe and north steppes, on the other, is bound to increase accordingly. By this means the transformations of natural ecosystems of the main watershed of the Volga River Basin will follow the direction of prevailing of complication of phytocoenosis structures within the limits of the zonal geospace itself and each separate landscape kind alike. At the same time the concurrence between plant societies will be sharpened therewith not only on zonal-regional level, but on the topo- ecological chains of each landscape kind as well. The common dynamic tendencies of natural ecosystems, which drop their tolerance, should accordingly increase.

The gradient (ordination) analysis was used to establish the predicted changes in the *two branches of small biological cycle, production and detritus*, in broad-leaved, mixed, and light-coniferous forests of the Middle Volga Region. The general model scheme escribes the driving forces of climate-genic successions – *the fundamental mechanism of transition from functional changes to structural transformation of ecosystems under the effect of global warming.* Under stable development of thermo-arid climatic signal, transformation of forest ecosystem into steppe one proceeds by the following scheme:

a) acceleration of the "work" of detritus branch of metabolism with concurrent decrease of ecological production efficiency (ratio of the productivity to phytomass)

↓

b) disturbance of the biological cycle balance (closure) as the most important condition of stable functioning of an ecosystem

↓

c) degradation and decomposition of forest community, its replacement first by arid open woodlands (typical forest-steppe) and then by grassy-steppe formation

↓

d) enhancement of the efficiency of autotrophic biogenesis

↓

e) attainment of the balance of creative and detritus branches of metabolism on a new ("forest-steppe" or "steppe") level of the functioning of ecosystem, with new stable state.

4.3 Changes in the landscape-zonal structure of the Volga River basin territory

In accordance with the system of phytocoenological transitions described above, one should expect a sequential northward shift of zonal and sub-zonal boundaries of function of natural complexes. This process must be most efficient in soil-plant cover on the territories of southern forest-steppe, including also northern steppe, and middle and south taiga sub-zones. Motley grass-cereal oak forests of typical forest-steppe will be most unstable and ready to be completely absorbed by total with time. Ultimately, on the place of the sub-zone total with time.

As a whole, the directed graphs plotted for all three prognostic periods (2050, 2075 and 2100) demonstrate a gradual northward shift of zonal and sub-zonal boundaries and the corresponding changes in the types of ecosystem functioning under the action of thermo-arid climatic trend. Objects-dominants and subdominants, whose appearance will be a prototype for transformations of most landscape-zonal systems, will be exclusively sub-boreal natural complexes: typical and southern forest-steppe and northern steppe (Figure 4). By 2100, the features of the forest-steppe will have become more and more characteristic of not only sub-taiga but also south and middle taiga sub-zones of the Volga River basin.

The most significant shift of landscape-zonal conditions towards aridization is outlined at the first and second stages of the forecast period (Figure 5), when the increase in atmospheric precipitation will be still low as compared with the temperature increase, which will result in a rather abrupt fall of coefficient of humidification – first in the middle and south taiga and then in the typical and southern forest-steppe.

Thus, the starting signal of the warming will be the most effective ecologically and territorially. Already in 2050, the average taiga regime of ecosystem functioning will almost completely move to the north, beyond the boundaries of the Volga River basin. Fur- ther shifts of landscape-zonal boundaries will be much less due to increasing precipitation, particularly in 2100, slowing down the decrease of F_{hum}. Because of this very reason, a counter transgression of the subzones of south and even middle taiga to the territory of broad-leaved forests is possible.

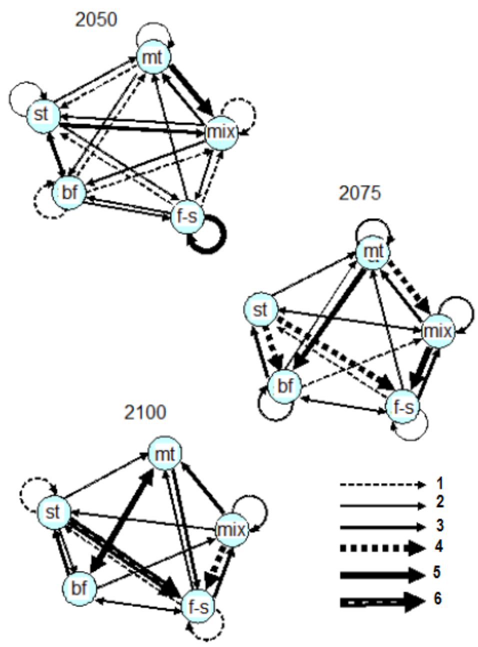


Figure 4 The direction and speed of the functional transformation for landscape-zonal systems of the Volga River basin for different forecast periods, according to the GISS-1993 climate model. Systems: mt – middle taiga; st – south taiga; mix – mixed forests; bf – brouadleaf forests; f-s – forest-steppe. Transition probabilities: 1 – ≤ 0.20; 2 –0.21÷0.30; 3 – 0.31÷0.40; 4 – 0.41÷0.50; 5 – 0.51÷0.60; 6 – 0.71÷0.80.

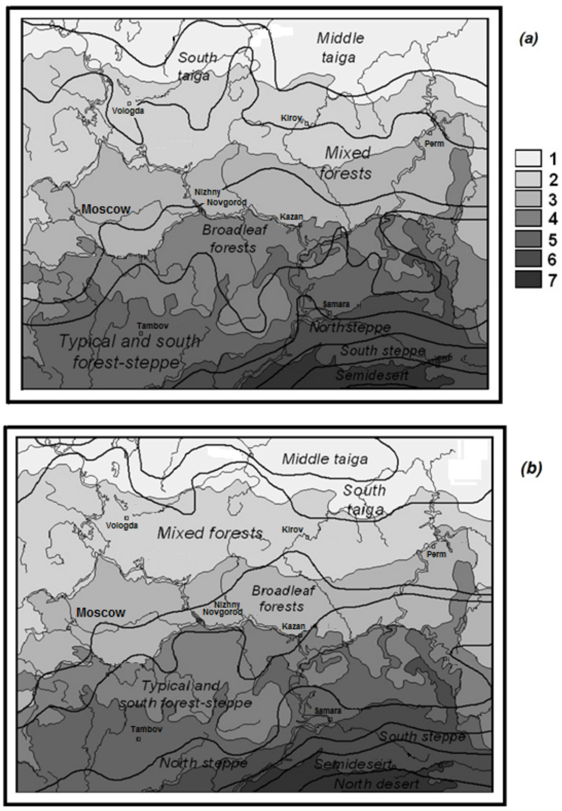


Figure 5 The zonal landscape and environmental conditions of the Volga River basin and its environment, predicted for 2050 (*a*) and 2100 (*b*) years according to the climate model GISS-1993. Areas of modern natural zones (sub-zones): 1 and 2 – middle and south taiga; 3 – sub-taiga; 4 – broadleaf forests; 5 – typical and southern forest-steppe; 6 – northern steppe; 7 – southern (dry) steppe.

So, the following equifinal transformations of the zonal structure of the Volga River basin may be anticipated. First, two zonal types of the environment will be most developed territorially: mixed forests, on the one hand, and typical and southern forest-steppe, on the other hand. This forest-steppe belt will become broader all along. Consequently, by the middle of the 21st century, almost the whole territory of the main catchment area of the Volga river basin will have occurred in sub-boreal climatic conditions. At the same time, if in the first 30 years the transgression will show itself mostly in the mixed and, to a lesser extent, broadleaf forests, in the year 2030, the whole forest-steppe zone will be of no less priority and become the predominant absorbing state at the end of the forecast period.

Second, the nemoral sub-zone will abruptly get narrower and change its location, having moved beyond the known oro-climatic barrier – a latitudinal segment of the systems of valleys of the Oka, Volga and Kama Rivers. The territory of modern broad-leaved forests will be completely adsorbed by typical forest-steppe formations (meadow steppe), which partially expand even over the pre-Ural taiga. The oak-lime communities meanwhile will show transgression first to the south and then to the middle taiga, creating new mixed phytocoenotic structures and thus extending the total area of sub-taiga zone.

Finally, the bioclimatic contrasts in the southeast of the region (in its most continental part) will sharply intensify, which will result in a considerable closing in of zonal and sub-zonal boundaries in the south of Pre-Urals, up to the appearance of the zone of semideserts at the latitude of Orenburg. The forest-steppe zone will be gradually losing its stability: the degree of its stabilization from the first to third forecast stage would decrease from 50–60% to 10–20%. Accordingly, it will start to transform into steppe in its southern and particularly southeast regions.

The predicted thermo-arid bioclimatic trend is in harmony with the global scenarios of natural zonality obtained from various models, including the GISS model, for double CO_2 concentrations in the atmosphere [10, 32], i.e., for the year 2100. The maps and schemes plotted by the authors show that the forest-steppe and steppe formations should intrude very deeply into the forest zone of Eurasia, reaching the latitude of the city of Kirov in the east of the Russian Plain and the mouths of the Ob and Yenisei Rivers in Western and Central Siberia. At the same time, the farthest expansion of "steppe areas" on the European territory of Russia is anticipated, along with the Central Russian and the By-Volga Upland.

Prognosis results, quite similar to our model, have also been obtained for the territory of the former USSR [33, 34]. This concerns, in particular, significant (2.5–3.4-fold) cutting of the taiga zone anticipated by the 10-the 30 s of the 21st century. Moreover, a 10-fold extension of the area of broad-leaved forests seems to be unlikely. We could also agree that by 2100, when the value of global warming will have reached 1.4^0, the landscape-ecological conditions of mixed forests will prevail on the territory of the Volga River basin. According to the calculations [35], the zonal conditions of coniferous-broadleaf forests are expected to extend to 62–63^0 N in the east of the Russian Plain already in 2010, which goes far beyond the northern boundaries of the Volga River basin. Our scenario, as a matter of fact, assumes such a possibility, but only after the middle of the 21st century.

5 Conclusion

As a whole, the results of scientific search presented in the monograph suggest that the regional approach to the assessment of global changes may become one of promising methodological aspects of geographical ecology called to solve global ecological problems. The results obtained are not only of scientific and/or methodical interest. They obviously will have certain practical significance also for the economic regions of forest and forest-steppe zones of the Volga River basin. The data on the condition of forest and forest-steppe ecosystems and prognostic assessments of their forthcoming changes may be used to develop the bases of preservation, reproduction and rational use of forest resources, to form a network of protected and recreational territories (nature reserves, wildlife refuges, national parks), which is particularly important for the regions with critical existence conditions for vegetation, including the zone of forest-to-steppe contact.

The author hopes that scientific-methodical and theoretical developments presented in this research may be included into the methodological arsenal of researches in regional dynamic ecology as a rather new scientific field called to solve the problems of bioecological and geosystem monitoring by creation of regional models of global environmental changes.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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