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RESEARCH ARTICLE

Advancing the methods of geo-ecological forests monitoring under global warming

Erland G. Kolomyts

Institute of Basic Biological Problems, Pushchino Science Center of Russian Academy of Sciences, Pushchino 129290, Russia

Correspondence to: Institute of Basic Biological Problems, Pushchino Science Center of Russian Academy of Sciences, Pushchino 129290, Russia;
Email: egk2000@mail.ru

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Abstract: One of the most dynamic natural processes on the planetary scale are changes in the global climate caused by changed chemical composition of atmosphere, with the corresponding demonstration of greenhouse effect. Global geosystem monitoring is most up-to-date and actually realizable on the scale of individual ecological regions. However, natural processes and events on the regional hierarchic level are characterized by the greatest diversity and high discreteness, therefore the regional response of global climatic changes inevitably takes the form of multiple reactions of vegetation, soils and landscapes as a whole to background climatic signals. The regional and local levels of geo-ecological prognoses still have not been developed enough due to insufficiency of factual material and methodical difficulties of the transfer of hydro-climatic prognosis from global to regional and local. The report expounds the main statements of original topo-ecological concept of prediction: "Global Changes on the Local Level", as a basis of terrestrial bio-ecological and geosystem monitoring under global anthropogenic climatic changes. This concept makes it possible to carry out local empirical simulation of the regional bioclimatic trend and thereby reveal the mechanisms of transmission of global and regional climate signals to the local level. Objects of research are forest and forest-steppe landscape-zonal systems of the headwater of the Volga River basin. They are included in the boreal ecotone of Northern Eurasia as the territory most sensitive to climate change and, accordingly, very favorable for the development of theory and methods of environmental monitoring. The conservation and reproduction of forest resources under changing climatic conditions at the southern boundary of temperate forest zone, where forest communities are in conditions close to critical, is one of the fundamental ecological problems. The strategic goal of monitoring research is to reveal the environmental potential of sustainablility of forest ecosystems in the context of modern global warming.

Keywords: forest ecosystems, environmentally sustainability, global warming, geosystem monitoring, geo-ecological prognoses, terrestrial bio-ecology

1 The problem of global changes on the regional and local levels

The concept of monitoring was first mentioned in 1972 at the UN Stockholm Conference on the Environment in the report of R. Mann. In Russian scientific circles, the theoretical foundations of environmental monitoring were laid down in the works of Innokenty P. Gerasimov and Yury A. Israel. Among the main tasks of modern human ecology, one should name, firstly, the assessment of the state of the quality of the natural environment, characterized by geophysical, geochemical and biotic parameters, and secondly, the establishment of the ecological reserve of geo(eco-)systems and the maximum allowable anthropogenic loads in order to develop principles of environmental regulation, taking into account economic and social aspects. These issues are included in the list of tasks of *geo-ecological monitoring*.

The efficiency of the ecological approach to nature research is as follows: first, the entire closed contour of forwarding and backward connections in the object – environment system (not only the closest, direct, but also remote, indirect) is studied and, second, now it is possible to predict the state of necessary natural components under the anthropogenic impairment of particular elements of ecological connections. The latter circumstance should be especially emphasized because the necessity of wide introduction of the ecological concept into Earth sciences and the practice of monitoring [1, 2] is determined by the increasing energy availability for mankind and the dramatic increase in human technogenic impact on nature, which occurs before our eyes.

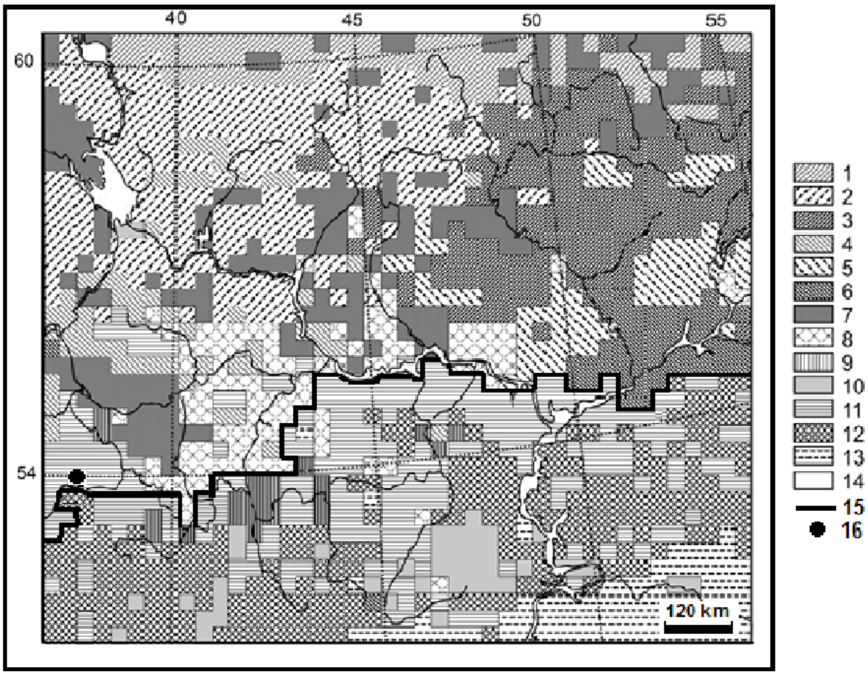

Figure 1 Raster base map of zonal-provincial groups of indigenous plant formations (modern + restored) on the territory of the main drainage basin of the Volga basin. The map is designed and compiled with the participation of L.S. Sharaya. Symbols of 1–14 see in the Table. 1. 15 – the Main Landscape Border of the Russian Plain. 16 – position of the By-Oka-Terrace Biosphere Reserve.

The implementation of the ecological approach in many natural sciences is associated with the better understanding of the role of biological components of landscape in its stabilization and self-regulation, as well as with the drastic aggravation of the problem of nature protection in recent decades under the conditions of worldwide scientific and technological revolution and powerful social and cultural shifts in human society. The development of the geo-ecological concept manifests itself in filling the old term “landscape science” with the new ecological content. As is known, global geosystem monitoring is most up-to-date and actually realizable on the scale of individual ecological regions. However, natural processes and events on the regional hierarchic level are characterized by the greatest diversity and high discreteness, therefore the regional response of global climatic changes inevitably takes the form of multiple reactions of vegetation, soils and landscapes as a whole to background climatic signals. So far there is no any distinct notion of this multiplicity, because the measure of sensitivity of soil-biotic components to climatic changes in different zonal-climatic and geomorphological conditions has not yet been estimated.

The known to date prognostic-ecological developments are, with few exceptions, of a very schematic character and aimed mainly at the assessment of general future condition of biosphere as a planetary system by quite a limited set of geophysical parameters (for the most part, air temperature and atmospheric precipitation). Accordingly, prognostic and paleo-geographical maps are too small-scale and cartographic prognosis confines itself to schematic demonstration of changes in the boundaries of natural zones and areals of some forest species. The regional level of geo-ecological prognoses still has not been developed enough due to insufficiency of factual material and methodical difficulties of the transfer of hydro-climatic prognosis from global to regional. Ecological safety of large territorial sub-units of the continental biosphere significantly depends on the state of the zonal-regional types of natural ecosystems, first of all forest cover. Therefore the problem of maintenance of forest ecosystems and reproduction of forest resources on the southern boundary of 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 East-European countries, where the wide transitional zone from forest to steppe, i.e. 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.

We will consider all regional and local problems of ground-based geoecological monitoring using the example of the main catchment area of the Volga River basin as an industrial and demographic "core" of European Russia. (see in Figure 1) shows a basic raster map of zonal-provincial groups of plant formations of the Volga River basin. The map was compiled on the basis of known geobotanical materials from 1974–1987. These materials have not lost their content to this day. Based on the data of the state records of the Forest Fund of the USSR, it was established [3] that for the period from 1968 to 2008 in the European part of Russia, the areas of land covered and not covered with forest changed by 6–8%. Insignificant changes have also occurred in the species structure of forests: the share of coniferous species in the composition of forested lands decreased by 4%, while the share of softwood species increased by 5%. Thus, it can be assumed that modern global warming has not yet significantly changed the structure and ranges of classes and groups of forest formations in the Volga basin (despite the fact that such changes could already have occurred on a local scale). (see in Table 1)

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

Phytocoenological units, by Gribova et al. [8]		Groups of plant formations		
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 small-shrubs	1
		South taiga	Spruce small-shrub-grass	2
		Sub-taiga	Broadleaf-spruce complex nemorose-herbal	3
	Kama – Pechora – West Ural region	Middle and south taiga	Fir-spruce and spruce-fir grass-small-shrub, 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) small-shrub-grass	8
			Broadleaf-pine and pine complex, 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 combination of oak forests	12
		Southern forest-steppe	Rich herb-sheep's fescue-feather grass steppes, with oak copses	13

The ranges of each phytocoenological group on the map (Table 1) included indigenous forest communities (dark and light coniferous, mixed) – both modern and restored on the site of long-derivative (small-leaved – birch and aspen) forests, as well as agro landscape complexes. Thus, this map is *a model of the potential bioclimatic forest system of the Volga River basin*. It reflects *the zonal-provincial phyto-climatic structure of this territory* and can serve as a basis for constructing background bioclimatic forecast maps. Based on it, forecast estimates of the carbon balance of forest cover hypothetically represented only by indigenous formations may be given, which is very important for comparison with the predicted carbon balance of real forests.

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

This report implements a landscape-ecological approach to the development of a monitoring system. It expounds the main statements of original topo-ecological concept of prediction: "Global Changes on the Local Level", as a basis of local bio-ecological and geosystem monitoring under global anthropogenic climatic changes. It is described natural ecosystems of the local (topological) level (landscape facies, or biogeocenoses) as the initial objects of study, since the origins of the mechanisms of the biosphere's reaction to external influences are concentrated here [4, 5]. As an example, we present the system of forest biogeocoenoses in the By-Oka-Terrace Biosphere Reserve (Table 2). The peculiarity of the landscape-ecological approach to monitoring is that, firstly, this approach concerns the entire complex of natural relationships (both direct, ecological ones, and indirect, geographical ones), and secondly, it covers not only inter-component interactions, but also territorial patterns of changes in environmental ties, i.e. considers natural ecosystems in their spatially distributed parameters. The scientific search presented in the book set one of its goals to develop scientific and methodological foundations for spatial functional monitoring of forests based on empirically established local and regional landscape-ecological relationships, which are considered as mechanisms of the metabolic response of forest ecosystems to certain climatic trends. This is the experimental nature of local geosystem monitoring.

The problem of conservation and reproduction of forest resources under current global warming is the most acute in the southern boreal belt and in the northern sub-boreal belt, i.e. in the zonal transitions from forest to steppe. The ecological role of forests is par- ticularly important, firstly in the forest-deficient regions, which include practically the entire middle belt of the European Russia [6]. The requirement to preserve the reproduction of forest resources at the southern border of the mid-latitude forest zone, where forest communities are in the near-critical states, is among the fundamental ecological problems [3]. It has been always of high priority for European Russia, within which there is a vast transition band from forest to steppe, i.e. the boreal ecotone [7], is a part of the industrial and demographic "core" of the Russia. It is a rather extensive transition zone from the boreal (predominantly coniferous-forest) belt to the sub-boreal (forest-steppe and steppe) one. Here, the forest formations are under modern hydrothermal conditions close to the critical ones. (see in Table 2)

Table 2 Groups biogeocoenoses (landscape facies) in the territory of the By-Oka-Terrace Biosphere Reserve

No. of facial groups	Brief description	The symbol
1	Pine-birch forests, with aspen and lime, on gently bulging sandy inter-fluves and high parts of slopes	
2	Pine-spruce and spruce-pine forests on the gently sandy-loamy water-sheds	
3	Pine-lime-oak and pine-lime forests on watersheds (with small depth of carbon eluvium)	
4	Lime-aspen-birch forests on high and middle parts of sandy-loamy slopes (with small depth of carbon eluvium)	
5	Spruce and spruce-pine forests on middle and lower parts of sandy-loamy slopes	
6	Swamped coniferous and small-leaved forests on the floodplain depressions and small stream valleys	

The main catchment area of the Volga river basin is to serve as an object of local and regional monitoring of the sustainable development of forests in the southern margin of the boreal belt of the East European sub-continent under the conditions of modern global climate change. This territory is included in three world centers of extreme anthropogenic destabilization of the natural environment, with the loss of up to 80–90% of the forest cover area and with the dominance of secondary associations [6]. Even in the taiga zone of European Russia, by the beginning of the 1990s, slightly more than 60% of forest areas remained undisturbed. In the remaining Upper Volga-Oka forests, more than 50% loss of phytomass occurred. Based on processing the recent satellite data from the digital Forest Map [9], it has been established that no more than 43% of the Oka river basin is covered with continuous and open forests. Crown density varies from 38–45% to 56–63% in the basin with an average of 50.7%, which brings a considerable part of forest areas in the Oka basin to a thin hemi-xerophytic state.

General thinning of the stands and defoliation of the crowns have resulted from fungal diseases of the trees, infestation by entomophytes and desiccation of some species (in particular spruce and oak), as well as from forest management stresses [10]. Generally there was an overall increase in forest cover across European Russia between 1961 and 2000, however in the boreal belt the area of small-leaved forests increased twice as much as that of coniferous forests [11]. The replacement of indigenous (climax) zonal forest formations of the Oka river basin (dark coniferous, mixed, broadleaf) by the secondary small-leaved communities (birch and aspen forests) caused by centuries-long intensive forest and agricultural activities has led to a decrease in the efficiency of solar energy use for production of living phytomass [3] and, consequently, to a significant loss of environmental resources by the forest cover of its feedback to the climate through the mechanisms of carbon cycle regulation, according to the concept [6, 12]. At the same time, dynamics of forest communities has increased – their sensitivity to perturbing hydrothermal signals has increased and successional shifts have accelerated, seeking to return them to their previous (or new) sustainable state [3].

Monitoring studies are aimed primarily at solving the fundamental environmental problem of our time – the preservation of forest ecosystems in a changing climate and the reproduction of forest resources on the southern border of the forest zone of temperate latitudes. These studies are also intended to make a certain contribution to the development of scientific and methodological foundations for combating further deforestation ("anthropogenic desertification") of this area of the Center for European Russia and reforestation on degraded lands. This direction of research will correspond to the UN Sustainable Development Summit (2015) "Protection, restoration of terrestrial ecosystems, efficient management of the forests, desertification control".

The world literature marks that research of the functioning of boreal forests in the changing global climate is hindered by uncertainties in the data specifically for Russian forests [13]. Some authors also state that current understanding of ecological processes in the boreal forests is still in its infancy; hence more attention should be paid to these forests [14].

2 Current state of the concept of geo-ecological monitoring in a changing climate

According to its classical definition, monitoring includes "... observations of the factors of impact and condition of the environment, forecasting of its future state and assessment of the actually predicted state of the natural habitat" [2, 11]. Meanwhile "... the problem of controlling (and managing) the quality of the environment relies on ecological forecasting, requiring the construction of ecological-economic models" (in place cited 16). General monitoring consists of two parts – bio-ecological and geo-systemic [15]. *Bio-ecological monitoring* includes the monitoring and forecasting of anthropogenic changes in individual (selective) natural phenomena and processes that are directly or indirectly related to public health. These changes can be both catastrophic and longer-lasting. For example, toxic indicators of air and water pollution can be related to an increase in the incidence of cardiovascular problems, infections and colds, etc.

Geo-system (geo-ecological), including the biosphere, monitoring is the second stage (block) of general monitoring, which serves as a necessary addition to bio-ecological monitoring. The main content of geo-system monitoring, as defined by I. P. Gerasimov [15], consists of: 1) a complex analysis of the state of geo(eco)systems as integral natural formations and as differential structural units of the biosphere; 2) an estimate of their resistance to external impacts, as well as forecasting of their anthropogenic changes. Extraction of anthropogenic component in the global changes of the environment is included in the strategy of transition to sustainability. Our research deals mainly with *geo-system monitoring* as a subject of ecological-geographical studies. Traditional geo-ecological monitoring considers the ecological consequences of mainly focal anthropogenic impacts on the environment: agro- and forestry, industrial, transport. Up to date, the most developed is the system of integrated background monitoring of anthropogenic pollution of the environments – atmospheric air, soil, surface water and vegetation [2, 16]. In recent decades, possible functional and structural transformations of the ecosystems and their components under the influence of anthropogenic climatic changes, including current global warming as an urgent environmental problem of mankind, have been actively studied [13, 17–22].

According to Gerasimov–Izrael conception, the whole system of environmental control can be summarised by the following formula: "observation (state assessment) – control (forecasting) – management (adaptation, feedback, regulation)". From the very beginning, Yu.A. Israel emphasized that monitoring in its full scope should include not only "tracking" (repeated observations), but "... also an assessment and prediction of the state of the environment ... and control of the environment quality" [2], i.e. implementation of its entire operational triad (see above). Unfortunately, this most important methodological provision of the doctrine of geo-ecological monitoring is rarely carried out, especially in regional and local environmental studies, although the term "monitoring" is mentioned every time. In both Russian and foreign literature on monitoring, the vast majority of works is limited to analyzing the initial (basic) state of natural and anthropogenic ecosystems and, at best, identifying cause–and-effect relationships between the dynamics of soil-biotic components and climate change as the basis for environmental forecasts. This simplification of the original concept of ecological monitoring can, to a certain extent, explain the fact that, as noted by A.A. Tishkov [23], the idea of developing background monitoring stations on the basis of Russian biosphere reserves has not yet been implemented.

Let us give some examples that outline specific ecological studies and characterize in one way or another only the first stage of geo-ecological monitoring. Planetary remote data on vegetation distribution and dynamics and the environmental maps based on them have been considered as a potential for monitoring and modeling the impacts of global climate changes on plant communities [21]. According to the BERMS Program, measurements of CO_2 fluxes over the boreal forests of Saskatchevan province (Canada) during 1993–2003 revealed a negative role of drought in carbon uptake by deciduous stands [20]. The range of similar studies in Russia is very significant. New approaches have been developed to estimate climate-controlled net products of forest ecosystems as an objective index of their response to climatic changes [24]. Seven-year year-round observations of CO_2 fluxes from derno-podzolic soils under forest and grassland vegetation were carried out in the Oka river basin [25]. This experiment has been named "multi-year monitoring" in its simplified interpretation. As a result of multiyear field measurements and the use of multispectral satellite information, the data were obtained on daily and seasonal dynamics of greenhouse gases in forest, swamp and fallow lands in the southern taiga of North-West European Russia. The models built enables us to predict the values of CO_2 fluxes at climatic changes [26]. Numerous experiments have been conducted to study the influence of modern meteorological and climatic conditions on the state, phenology and trends of plant communities in different regions of the Russian Plain and the Middle and Southern Urals. So, using the forests of Arkhangelsk region as an example, the experience of identifying signs of deterioration of physiological condition of the tree stands based on multi-spectrum satellite imagery and terrestrial forest survey data [27]. The study of the long-term dynamics of biosphere processes in the Central Chernozem Biosphere Reserve has made it possible to formulate some unsettled issues of their predictive interpretation [28].

Separate from the subjects of the above and many other similar studies are very informative works of the second stage of monitoring – on regional and planetary ecological and geographic forecast, as well as on prediction of the carbon forest balance. Here we can note the predictive scenarios of climate-genic changes in zonal and regional ecosystems of the Russian Plain, Western and Middle Siberia [29, 30]. A picture of general regularities of the global carbon cycle and the greenhouse effect of the atmosphere in Holocene and in recent period due to temperature changes has been described [31]. Based on climatic scenarios of the predictive models ECHAM4/OPYC3 and HadCM3, possible changes in the productivity of vegetation in Russia in the 21st century were calculated and mapped on the basis of its modern geophysical ordination [32]. Predictive analytical and mapping models of the carbon balance of Russian forests based on integrated ground and satellite information have been developed [33, 34].

Finally, let us turn to the third and final stage of monitoring – management (regulation). This stage is still mostly in the state of proposed definitions, conceptual hypotheses and proposed scientific and methodological programs. First of all, it should be mentioned the proposed concept of "climate geo-engineering" as a targeted change in the parameters of climatic system in order to prevent catastrophic ecological consequences of the global warming [21]. Such changes can, and have throughout the history of the biosphere, been caused by forest cover through regulation of the carbon cycle [12, 18]. Global predictions of the role of forest cover in regulation of the atmospheric greenhouse effect are presented in small-scale scenarios of the carbon budget of circumpolar boreal forests of Eurasia and North America based on correlation relations of their biomes with temperature and precipitation ranges [11, 14]. One of the most important ways to achieve the goals stipulated by the Paris (2015) Agreement on Climate Change [34] is to solve a twin challenge problem: absorption by forest communities of CO_2 from the atmosphere during global warming and their adaptation to these climate changes, which should ensure the effectiveness of adsorption itself through feedback interactive communication. In this regard, the proposed concept of "adaptation monitoring" is very constructive, which expands the existing climate monitoring system and represents its final stage as "monitoring of climate activity" – mitigation and adaptation [22]. Adaptation of ecosystems is understood a set of measures to ensure their sustainability and normal functioning in a changing climate. The global goals and objectives of sustainable development in Russia are analyzed from the point of view of the presence of a climate component in the relationship system. The expected impacts of climatic change on the forests of Russia and the mechanisms of forest adaptation are considered for the use of the latter as the means of mitigating climate signals. This is part of the concept of transition to sustainable forest management in Russia developed in the works [14]. This concept assumes management and the use of forests in such a way as to maintain their biodiversity, sustainability (elasticity) and productivity, as well as their ability to perform ecological functions – in our case, mitigation. The concept considers various models of vegetation-climate feedback and describes a system of sequential actions for sustainable forest management: substantiation of regional indices of forest sustainability, creation of a new unified system of forest inventory and operational monitoring, biophysical and economic assessment of ecosystem functions and services of forest communities on a zonal-typological basis, etc. In order to further develop forest science as a basis for sustainable forest management, the Program "Ecological and socio-economic threats of forest degradation in Russia and ways to prevent them" has been proposed [35].

In general, a concrete solution to environmental problems to assess the role of forests in mitigating global warming has not yet been widely used. Consequently, there have been few studies on the potential for this mitigation through forestry [11]. In the summary of the European Forest Institute "Forests of Russia and climate change. What Science Has to Say" only questions are raised about sustainable and climatically optimized forest management and reforestation to mitigate the effects of climate change and develop a "closed-cycle forest bio-economy" [13]. A rare exception is the detailed development of strategies for managing forests of US National Parks in order to increase their ability to bind atmospheric carbon and adapt to the expected climatic changes [36]. We will discuss this work in more detail below. A fluent(and very incomplete) analysis of Russian and foreign literature shows that each of the three triads of geo-ecological monitoring has already received independent scientific and methodological development, but integration of all these results into a single operational monitoring system remains very problematic. In addition, these studies are usually based on on simulation (continual, dynamic) modeling of the natural environment, which essentially does not go beyond the limits of out- and synecology, leaving out of sight the geographical (spatial) ecology. These are models with concentrated parameters; they do not provide a territorial sweep of supra-parcelular landscape units, (biogeocoenoses, stows, localities) in their organization and in response to external disturbances, and this is a certain limitation of simulation models. In or investigations, geosystem monitoring was be carried out on the basis of discrete empirical and statistical models, according to [37]. These models allow operating with a relatively small number of the most informative signs and obtaining results with a sufficiently high spatial resolution and, most importantly, predicting the behavior of forest biogeocoenoses in the form of integral formations, according to [38]. Favorably differing from simulation models by the ability to more fully describe the properties of geographical space, empirical-statistical models have their own significant disadvantages, which are especially noticeable in predictive ecological analysis. The main thing is their "uncertainty in time", but they allow for a quick assessment of the state of ecosystems and their changes over large areas [39]. In particular, they can adequately reflect the processes of stabilizing selection as a reaction of biota to climatic disturbances exceeding the threshold of its adaptation.

Therefore, it is proposed to carry out geo-system monitoring in the volume of ecological and geographical research, as defined by I.P. Gerasimov (see above). It is necessary to carry out a complete cycle of climate-genic monitoring "observation – control – management" on the example of a specific eco-region, with the development of a unified system of empirical and statistical modeling of the state of forest natural complexes in the past, present and future and the identification of appropriate direct and inverse forest-climate relationships. On this basis, it is necessary to reveal an ecological potential of the forests, ensuring the transition of forestry to an adaptive strategy. Such an ecological-geographical experiment of a local order was carried out in our study.

3 Scientific and practical significance of monitoring research

As already mentioned,the strategic goal of this study is to uncover the ecological potential of the transition to adaptive forestry based on revealing the mechanisms of forest ecosystem resistance and variability in changing climate. The problem is solved by implementing the full triad of geo-system forest monitoring "observation (state assessment) – control (forecast) – management (feedback, regulation)" on the trend of current global warming in the form of base and predictive ecological experiments, with the construction of analytical and cartographic empirical-statistical models. The research strategy is based on ideological and scientific-methodological provisions of the concept of geo-system monitoring as a landscape-ecological search system "Global changes at the local level" [3] put forward by the project manager. Spatial functional monitoring of the forests is conducted on the basis of empirically established local and regional landscape relationships, which are considered as the mechanisms of metabolic response of forest biogeosystems to climate trends, including current global warming. This is the experimental nature of the monitoring study itself.

In this aspect, the problem of geo-system monitoring remained until recently poorly developed, since, firstly, there was no factual basis required, and secondly – no sufficiently rigorous methodology of the local and regional landscape-environmental forecasting itself was created. In our scientific and methodological searches [7, 40, 41], the ways of solving these problems are covered in sufficient detail. Using the boreal ecotone of the Volga river basin as an example, we have substantiated the methods for determining those parameters of structural and functional organization of forest ecosystems of the southern boreal belt and the northern sub-boreal belt that are most sensitive to global climatic changes and which, therefore, can be used for regional geosystem monitoring [3, 7].

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

Objects of research are forest and forest-steppe landscape-zonal systems of the headwater of the Volga river basin. The conservation and reproduction of forest resources under changing climatic conditions at the southern boundary of temperate forest zone, where forest communities are in conditions close to critical, is one of the fundamental ecological problems. When developing this concept, the author faced significant methodical difficulties. The major of them was to assess the transformation of global climatic signals into local ones proportional to the scales of regional landscapes and their parts, down to biogeocoenoses. At present, there are actually no experiments on determination of the most probable directions and rates of distribution of hydrothermal signals from global to topological (local) level. The response of ecological niches of local ecosystems to the behavior of background climatic system is still not clear either. The regional hydrothermal trends are generally described by two initial parameters: temperatures and precipitation, the connection of which with landscape facies (biogeocoenoses) is weak and often statistically unreliable. It was necessary to establish the causal mechanisms of local response to global and regional signals by way of revealing transfer functions in landscape connections, which transform these signals at passing through the coupled ensembles of natural complexes.

The ways of solution of this problem were outlined in the course of realization of previous regional environmental forecast studies. It was established empirically that the main channel of connections of regional and local ecosystems with background climatic system passes through the summer soil moisture content which, on the one hand, serves as a rather reliable geophysical indicator of the state of ecosystems and, on the other hand, is the most powerful ecological factor predetermining their functional parameters. It has also been decided that the object of priority in the landscape-ecological prediction within a century must be not structural evolution of ecosystems but directed change of their functioning, i.e., the shifts in small biological cycle (phytomass production and degradation), which take the first several years in the taiga zone and are completed within a year in the subzone of broad-leaved forests. These typical times of functional relaxation approximately correspond to the carbon cycle duration in forest (live and dead) phytomasses and in mobile soil humus.

Discrete parameters of the small biological cycle determine the role of ecosystems in the biotic regulation of the carbon cycle and in the corresponding interactive effects of soil-plant cover on climatic processes. The minor biological turnover in forest ecosystems is known as one of the mechanisms that provide stability of natural environment according to Les Chatelier's principle. In respect to the carbon cycle in the biosphere, this principle is expressed by the following postulate: the state of the environment will be stable if any spontaneous increase of CO_2 content in the atmosphere is accompanied by an equal enhancement of carbon utilization by terrestrial and ocean biota. An apparent violation of Les Chatelier's principle is the transformation of biota from a carbon sink into a carbon source, i.e. when biota releases carbon dioxide into the atmosphere under external influence. Prognostic landscape-ecological scenarios of the nearest future of biosphere have been considered for the first time by the example of a large region – the Volga River Basin. The mechanisms of shifts in the mosaic structure of vegetation and soils have been revealed on the model territory under different scenarios of disturbing influence of climatic system, which are anticipated in the foreseeable future (to the end of 21^{st} century). All these models disclose the mechanisms of formation of local- and regional-level landscape-ecological systems, their natural and anthropogenic dynamics and evolutionary trends.

A significant place in complete cycle of geo-ecological monitoring is devoted to modeling the carbon cycle and the sustainability of forest ecosystems in a changing climate, which made it possible to quantitatively assess their role in the adsorption of greenhouse gases and mitigation of the climatic fluctuations themselves. The experience of using the methods of landscape ecology in the assessment of the biological cycle, carbon balance of forest ecosystems, and biotic regulation of the carbon cycle under climatic changes were stated. In this context, new propositions of the theory of stability of natural ecosystems were proposed and the methods for calculating functional stability of local and zonal-regional forest communities based on discrete parameters of the biological cycle were developed. Experience of the solution of the dual problem of adsorption and adaptation, according to Paris (2015) Agreement on climate changes [34], had been carried out. The specific and total carbon balances of forest formations of the Volga river basin were a basis for quantitative assessment of their ecological resources providing more favorable environmental conditions via carbon cycle regulation by forests. It should be emphasized that we are not talking about well-known experiments conducted at complex physical-geographical or biological stations, but about the experimental nature of spatial landscape-ecological analysis and forecast, which are carried out on the basis of large-scale landscape surveys at representative test sites characterizing a typical natural-territorial structure for given ecoregion. Cognition of local mechanisms of global changes in natural ecosystems is realized through a methodological construction with the working title "empirical simulation of a regional bioclimatic trend by ecosystems of a local level" (Table 3). The binary ordination of the zonal features of biogeocoenoses according to the leading factors of their formation was carried out on the basis of such spatially ordered series of their upland and extra-zonal categories that can be adequate to the vector of predicted climate changes. Through this methodological construction, the main regularities of the refraction of the zonal-regional bioclimatic background by local geomorphological and hydro-edaphic factors and the formation of the so-called regional systems of local natural zonality have been established. Such systems are capable of imitating the main directions and scales of soil-phytocoenotic rearrangements, thereby creating an empirical basis for predictive landscape-ecological constructions. (see in Table 3)

Table 3 By-Oka-Terrace biosphere reserve. Percentage distribution of groups of biogeocenoses in the space of location types (matrix of normalized partial coefficients of connection, in Vlasov et al. [28])

Types of local sites	Groups of boigeocoenoses (see Table 2)					
	1	2	3	4	5	6
TE	**48**	**55**	21	7	11	
E	39	30	12	**32**	12	
T	13	15	**35**	16	**46**	
TA, A			**32**	45	32	
Saq						**50**
EA						**50**

Note: Types of local sites: TE – transeluvial; E – eluvial; T – transit; TA – transaccumulative; A – accumulative; Saq – superaqueous; EA – eluvial-accumulative. Ecological dominants are highlighted in bold.

We have constructed a hydro-thermal series of flat-interfluve and extra zonal topo-ecosystems in ascending order concerning aridity. This series may be presented (based on self-similarity of the operational system) as a certain analog of the respective background climatic changes (trend). Thus, using the vector spectrum of *topological polyzonality* (see Table 3), it is possible to present realistic scenarios of the response of local ecosystems to some particular shifts in the regional climatic system and to outline the respective chains of local landscape-ecological transitions.

4 General direction of scientific research

The goal can be achieved by solving the following specific objectives:

1) study of the mechanisms of functional and structural organization of forest ecosystems in study region as objects of regional geosystem monitoring in conditions of zonal transitions from the boreal belt to the sub-boreal one; identification of forest phytocoenoses that are closest to the zonal climax and therefore can serve as priority objects of global biosphere monitoring;

2) empirical-statistical modeling of chain reactions in the system of inter-component and inter-complex landscape relations and the development of scenarios of forest ecosystem transition to critical states according to the main discrete parameters of the biological cycle describing primary production process and decomposition of dead organic matter;

3) conducting numerical experiments with ecological niches of forest biogeocoenoses on past, present and future climatic trends to reveal the mechanisms of transfer functions – from shifts in the background climatic conditions (atmospheric humidification) through hydrothermal soil parameters (edaphic humidification) to functional and structural characteristics of vegetation;

4) study of the long-term hydrothermal regime of the soil at the stationary observation site in order to assess functional response of forest ecosystems of the model area to inter-annual fluctuations in meteorological conditions; the latter can simulate to some extent the long-term (intra- and secular) climate change, if one or another meteorological fluctuation becomes the multi-annual norm;

5) spatial and temporal analysis of the parameters of the resistance of forest ecosystems as integrated indices of their adaptation to climate signals; revealing the mechanisms of functioning of ecosystems that determine the driving forces of regulation of the carbon cycle by forest cover as an ecological potential of their sustainable development;

6) construction, based on the results of analytical modeling, of large-scale basic and predictive maps of structural and functional characteristics of forest biogeocoenoses for selected sites of given regional system using multiple regression, geo-morphometric methods, remote elevation data, NDVI and forest cover structure;

7) creation, based on the final results of research, of a working algorithm for climate-genic geosystem monitoring of the forests, in which the analysis tool is an operational system consisting of the stages of observation, prediction and management (regulation), identifying the environmental effects of feedback control, including mitigating effect of the forest cover on the current global warming by regulation of the carbon cycle;

8) development of analytical models of functional properties of boreal and non-moral forests of given region; calculation of the maps based on them, describing the ecological potential that favors forestry transition towards an adaptive strategy.

The complexity of monitoring is largely due to the multifactorial nature of climatic system impacts and the multiple responses of different-order landscape structures and their elements to the same global and regional climate signals. Consequently, the uncertainty of the impact of global changes remains high [18], with frequent "adaptation deficit" of forest ecosystems to these changes.This highlights the problem of hierarchy of the scale of the ecosystem response and its spatial integration. Biosphere reserves as the territories for monitoring spontaneous, including globally anthropogenic, changes in the biosphere characterize in each region not only zonal-regional background of the territory, but typical diversity of local deviations from this background as well, which can imitate background characteristics of other regions, often quite distant. The diversity of biogeocoenotic structures of the regional ecosystems should correspond to the diversity of their response to global changes, which requires a conjugated multidimensional analysis of the structure and functioning of forest ecosystems.

A ragional system of geo-ecological monitoring can only be based on the achievements already made in the practice of studying and regulating the state of the environment [42]. This makes it possible to determine a certain primary "norm" of this or that variable of the state, as well as to assess maximal limits of its changes [28]. The landscape-ecological approach to the development of geo-ecological monitoring considers natural ecosystems of the local (topological) level (landscape facies, or biogeocoenoses) as primary objects of research. As is known [4, 5], the origins of the mechanisms of the biosphere's reaction to external influences are concentrated here. The peculiarity of the landscape approach to monitoring also lies in the fact that it, firstly, concerns the entire complex of natural relationships (both direct, actually ecological and indirect, geographical) and, secondly, it covers not only inter-component interactions, but also territorial consequences of changes in ecological binds, that is, it considers natural ecosystems in their spatially distributed parameters.

Geo-system monitoring in its full execution is a complex ecological-geographical study, so the creative team involved in this work should be interdisciplinary, covering the main branches of physical geography – geomorphological, phytocoenological, soil, geochemical, microclimatic. The synergistic effect of interdisciplinary research will be achieved to some extent by a generalizing landscape-ecological approach, with analytical and cartographic modeling of all three stages of monitoring "observation – control–management".

5 Working algorithm for ground geo-ecology monitoring

Carrying out all three stages of geo-ecological monitoring, according to its classical definition by Israel-Gerasimov (see above), allows: 1) to identify the climate-genic dynamics of the functioning, structure and carbon regime of the boreal and nemoral forests of the studied region for the entire previous (basic) period; 2) to make a forecast for the forthcoming 25–50–100-year period of ecological consequences of the indicated forest characteristics in the light of expected global climate changes; 3) to assess the connection of the functioning state of forest ecosystems and the climate by estimating their carbon balances as interactive mechanisms for regulating climate signals, including mitigation of global warming.

Let us briefly describe the research strategy of the geo-ecological monitoring – "observation–control–management", with examples of some of the results of our research in the By-Oka-Terrace Biosphere Reserve. It is located in the Middle-Oka river basin (see Figure 1) and is part of regional ecosystem "Russian Forest". According to the landscape surveys for two periods (1998 and 2022), a mathematical and cartographic analysis of the biogeocoenotic structure of the By-Oka-Terrace Reserve territory will be carried out, and the maps of productivity and stability of forest biogeocoenosis was be constructed for these two spatial and temporal sections. These analytic and cartographic models describe the spatial structure of the forest biogeocoenosis states of the reserve in the current period of global warming – 1985–2022.

5.1 The first stage of monitoring – observation (*state assessment*)

The resulting data bank includes six structural and functional blocks: hydro-geomorphological, soil morphological and geochemical, phytocoenotic – structural and functional, landscape-geophysical. A full processing of the materials of field observations and measurements is carried out, with the initial data sets acquisition for subsequent empirical and statistical modeling of the structural and functional state of forest biogeocoenoses at the current stage of their syn-genetic and climate-related dynamics. In geo-system monitoring, the assessment of the climate-related change in the conditions of forest biogeocoenosis of the reserve as elementary bio-chorological units according to [4], is first carried out partially by individual phytocoenotic and soil characteristics. Speaking about the landscape monitoring analysis, it can be represented by the analysis of climate-related changes in three groups of invariant indicators of the structural and functional organization of biogeocoenosis. These groups are as follows: 1) numerical parameters that characterize the degree of mutual equivalence of the geo-component blocks mentioned above, i.e. the closeness of interconnections (primarily the connections of biotic components with the characteristics of abiotic environment) as an indicator of the territorial integrity of the geo (eco) system as reported by [5]; 2) the main discrete indicators of metabolism – primary productivity and litter-all index, which characterize, respectively, the efficiency of the use of the substance and energy resources of the environment by phyto-biome and the output of the detritus branch of the biological cycle; 3) parameters of the functional stability of geo(eco) systems [41], labile (phytocoenotic) and inertial (soil-biotic), as integral indicators of their ecological reserve, or assimilative capacity [2]; these parameters determine the behavior of phyto-biome and soil organic matter in a changing abiotic environment. The climate-related transformation of the listed invariant functional indicators of forest biogeocoenosis have to show the corresponding violation of the ecological balance that was achieved earlier.

The vast majority of modern forest communities of boreal ecotone od the Russian Plain undergo various age stages of restorative successions after a long period of deforestation, which lasted almost until the end of the XIX century [10, 43]. This endogenous successional-restorative dynamics of forest communities inevitably overlaps with the exogenous structural and functional transformations caused by inter-decadal climatic signals. Endogenous processes either enhance or, conversely, weaken these transformations. So, the first step in the geosystem monitoring will be extraction of the climate-related structural and functional changes (ΔQclim) of the parameters of the state of this group of forest biogeocoenosis from the total amount of these changes (ΔQtotal) that occurred over the precedent period of time. To achieve this, it is necessary to know the magnitude of the age changes in the parameters of the state of biogeocoenosis during the time interval under review (ΔQage). In this case these changes are a "black box" (in cybernetic terminology) and include two main components: a) successional (self-healing, or demutational) trend of the forest community; b) the dynamics of interspecific and inter-population interactions in the forest biogeocoenosis. The procedure for extraction of structural and functional exogenesis in a forest community has the following form:

$$\Delta Qclim = \Delta Qtotal - -\Delta Qage \tag{1}$$

Here is an algebraic subtraction, and the signs of each term of the right side of the equation should be taken into account. For example, with the ratio of absolute values (–ΔQtotal) > (+ΔQage), the calculation model will show a negative value of climate-related changes in this parameter of the state of biogeocoenosis. In another case, this negative environmental effect can be overlaid by a positive successional-restorative trend and then we get +(ΔQtotal). And vice versa, when ΔQtotal < ΔQage (in absolute value), we always get negative values of the parameter ΔQclim. The calculations of the parameters ΔQage are planned to be carried out on the materials of the landscape mapping of 1998 on the basis of the known properties of ergodicity (spatial-temporal self-similarity) of natural ecosystems. (see in Table 4)

Table 4 The By-Oka-Terrace Biosphere Reserve and its encirclement. Calculation of climate change total productivity of forest biogeocenoses for the period 1998–2022, based on data from two large-scale landscape and environmental surveys

Groups of biogeocoe-noses (see Table 2)	Age of forest community, years	Total productivity (PC), t/ha· year	
		calculated (according to the conditions of 1998), (PC)age	real (total), (PC) sum, in 2022
1	51	11.65	11.98
	122	11.11	10
	111	14.23	11.16
2	90	7.5	9.84
	119	13.09	11.11
	121	12.4	11.31
3	89	12.5	12.28
	40	18.7	13.98
	60	15.38	13.42
	71	13.85	12.69
	139	12	10
	104	12	11.26
4	51	12.25	13.57
	92	8.62	12.39
	75	11.11	13.22
	72	11.54	12.76
	51	14.52	13.49
	57	13.5	12.98
5	106	13.5	11.8
	121	14.54	11.68

As an example, we present the results of calculations of exogenous (climate-genic) changes in the total annual production (PC) of forest biogeocenoses in the By-Oka-Terrace Biosphere Reserve and its surroundings over the last 24-year period (Table 4). We used materials from the basic landscape-ecological survey of 1998 and the repeated selective survey conducted in 2022 for a certain set of ecosystems-analogues from each biogeocoenotic group (see Table 2). Previously, it was found that the density of the forest (by the mass of the forest stand) closely correlates with the age of the stand, so the influence of the density of the forest on its specific productivity was taken into account in an implicit form. According to the adjacent to the reserve st. Kashira (average linear trends), during the considered period of global warming (1998–2022), the average temperatures of the warm and cold periods of the year increased by 0.8^0 and 1.5^0, respectively, while the increase in annual precipitation was insignificant – about 30 mm. This led to a decrease in the average July reserves of productive moisture in a 50 cm soil layer from 67 mm to 52 mm. Thus, the thermo-arid climate trend was evident.

Under these conditions, the groups of forest biogeocoenoses of the reserve that we identified were quite clearly differentiated by climate-genic changes in overall productivity (see Table 4, last column). It turned out that global warming at this segment of its trend favorably affected the functioning of only secondary forest communities (birch and aspen forests) and negatively affected the state of primary associations, both boreal (spruce and pine) and sub-boreal (pine-broadleaf and broadleaf).

5.2 The second stage of monitoring is control (forecast)

Analytical and cartographic landscape-ecological forecasting is carried out according to the methods, which we designed and accurately described in [3, 40]. The strategy of the landscape-ecological prognosis was as follows: first to carry out an identification of picked out ecosystem objects (either the zonal types and regional kinds of landscape or local nature complexes) to certain values of contemporary climatic conditions, and then to estimate the most probable transformation of revealed ecological niches of given objects according to of expected climatic changes for given prognostic date. Quantitative predictive analysis is carried out using the operations with hydro-thermal niches of regional or local ecosystems.

Predictive environmental calculations consist of three stages: (1) determination of ecological niches of objects in the space of modern and predicted (or reconstructed) climatic parameters; (2) procedures with the ecological niches based on their inclusion relations as descriptive vectors, giving the probabilities of stability (stabilization) of each object and its transitions into other objects according to the given climatic trend; and (3) determination (by methods of the theory of Markovian chains) of relative rates of functional transformation and average times of complete or partial absorption of the metabolic state of a given object by the states of other objects. In conclusion, the methods of calculation and construction of average weighted (by territory) matrixes and directed graphs of landscape-ecological transitions. (see in Figure 2)

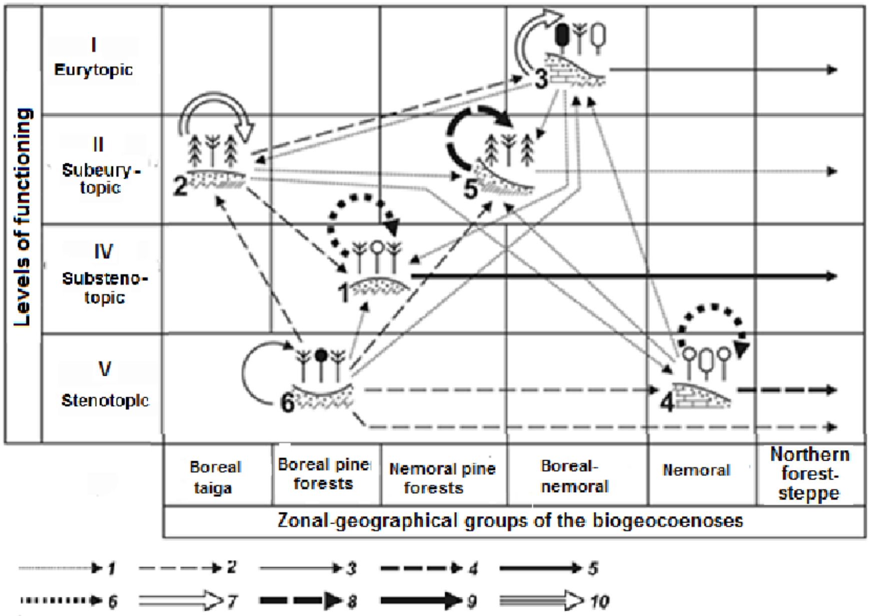

Figure 2 The By-Oka-Terrace Reserve. The thermo-arid climatic trend. The oriented graphs of functional landscape-ecological transitions, according to the forecast-climate model E GISS, 2150, between groups of forest biogeocoenoses with different zonal affiliations and at different levels of basic functioning. Transition Probabilities: (1) 0.10 or less; (2) 0.11–0.20; (3) 0.21–0.30; (4) 0.31–0.40; (5) 0.61–0.70. For designations of biogeocoenosis groups, see Table 2.

As an example, we present the results of forecast calculations of the climate-genic dynamics of forest biogeocenoses of the By-Oka-Terrace Reserve (see Table 2) for the year 2150 according to the climate forecast by the E GISS model [47]. This model gives a weakly expressed thermo-arid trend, with a decrease in the annual atmospheric umidity factor from 1.52 to 1.36. Nevertheless, mutual transitions of forest communities will be expressed quite clearly. So, swampy coniferous/small-leaved forests of river valleys will be replaced by 14–15% by meso-hydromorphic spruce and pine forests. The latter, in turn, will begin to transform at the same speed into xeromorphic birch-pine forests. In the areas of these forests there will be a significant introduction (by 48%) of nemoral northern forest-steppe communities.

We emphasize the experimental nature of this method. The researcher sets the input parameters to this operating system and receives the prediction of structural and functional states of the studied objects in this statistical sample, with identification of new non-selective objects. A scenario forecast-ecological analysis of the network of inter-component and inter-complex connections is carried out, as a system of translating of background landscape-geophysical signals and its transmission from the global and/or regional levels to the local level. Scenarios of disturbing influence can be set according to one or another variant of the global climate forecast for different periods. (see in Table 5)

Table 5 The By-Oka-Terrace Biosphere Reserve and its encirclement. Verification of predictive calculations of climate-genic changes in the total productivity (PC, t/ha·year) of forest biogeocoenoses for the period 1998-2022, based on the materials of two large-scale landscape-ecological surveys

Groups ofbiogeoco-noses, see Table 2	Base productivity (in 1998)	Predicted productivity in 2022		Real productivity in 2022	Climate-genic changes in productivity, (PC)clim, in 2022		
		by GISS model	by HadCM3 model		estimated by GISS model	by HadCM3 model	real
1	13.01	14.21	15.33	11.05	1.2	2.32	–4.24
	-8	-8	-8	-3	-8	-8	-3
2	13.1	14.41	!5.58	10.61	1.31	2.48	–3.40
	-7	-7	-7	-3	-7	-7	-3
3	13.62	14.6	15.5	12.2	0.98	1.88	13.95
	-7	-7	-7	-4	-7	-7	-4
4	13.44	14.6	15.62	12.97	1.16	2.18	12.56
	-9	-9	-9	-5	-9	-9	-5
5	10.78	13.2	15.37	14.02	2.42	4.59	1.77
	-7	-7	-7	-2	-7	-7	-2

Forecast calculations of changes in each functional parameter of forest ecosystems are carried out according to the following scheme. For each forecast period, the total amount of changes of this parameter (ΔQtotal) consists of its predicted climate-related changes (ΔQclim) and the expected changes driven by the age dynamics of the forest community over the same period (ΔQage):

$$\Delta Qtotal = \Delta Qclim + \Delta Qage \tag{2}$$

Same as in the first stage of monitoring, here is an algebraic addition, and the signs of each term of the right side of the equation should be considered.

The predicted scenarios of partial and complex functional parameters of forest biogeocenoses can be verified by empirical material. In table. Figure 5 shows an example of verification of such a forecast for overall productivity for some forest communities in the By-Oka-Terrace Biosphere Reserve for the period 1998–2022. It turned out that not only the moderate GISS climate model, but also the HadCM3 extreme model could not predict a decrease in productivity in the vast majority of forest communities: the positive values of Δ(PC)clim predicted by these models were not actually confirmed.

5.3 The third stage of monitoring is management (adaptation, feedback, regulation)

On the basis of geo-ecological forecasts, the problem of regulating the quality of the natural environment is solved, i.e. certain management of it with the help of negative feedback, the establishment of priority factors and effects of permissible impacts, as well as the probabilities of the risk of certain environmental consequences [44]. The problem of regulation of the quality of the environment is solved, in other words environmental management matter, with the establishment of priority factors and the effects of admissible impacts, as well as the probabilities of risk of certain environmental consequences. To achieve the sustainable development goals, first of all, effective adaptation of natural ecosystems to climate change is necessary. On the other hand, one of the most important areas of forestry, including sustainable forest management, is the use of forests as a tool for mitigating climate fluctuations with the aid of the carbon cycle [11]. This corresponds to one of the articles of the UN Summit (2015) – "... maintenance and restoration of land resources ... as a way of adaptation and fight against climate change" [10,45]. Adaptation and "mitigation" of biogeocoenosis can be attributed, as already mentioned, to monitoring of climate activity, according to [22]. It should be noted that the specific implementation of "monitoring of climate activities" remains very problematic. K.S. Losev reasonably noted: "If the biota as a whole adheres to the adaptation strategy, then there can be no biotic regulation. Each of the strategies is carried out in reality, and this can only be established on the basis of unambiguously interpreted empirical material" [**?**, 6].

The solution of the sustainable forest management (SFM) issues is most commonly associated with forest use scenarios, on the assumption of relatively constant values of carbon sequestration by various forest formations. Forests that are exposed to human influence are regarded as manageable , and the main factor of their carbon balance changes is considered to be the volume of timber production. Climate-related monitoring does not touch on forest management issues, and as a result, it has completely different criteria for sustainable forest management. Here "the transition to SFM ... is a transition to adaptive forestry" [16, 46]. We are talking about creating such adapted forest communities that ensure optimal regulation of the carbon cycle and thereby ensure their sustainability in a changing climate. That is how we can formulate the task of the ecological potential of forests as a necessary condition for the transition to adaptive forestry.

We find some general suggestions regarding ecological maintenance of adaptive forestry in the works [11], where the concept of transition to sustainable forest management in Russia is being developed. This concept involves the management and use of forests in such a way as to maintain their biodiversity, sustainability, and productivity, as well as their ability to perform ecological functions, including mitigation of the current global warming. These four indicators should be reviewed at the third and final stage of geo-ecological monitoring. According to the mentioned authors, the system of consistent actions of sustainable forest management should include: 1) analysis of vegetation respond to the climate; 2) calculations and description of regional indicators of functional stability of forests; 3) creation of a new unified system of forestry management and operational monitoring on a zonal-typological basis. The third paragraph in given monograph can be highlighted only in terms of formulating the problem.

It is also possible to use the methods for the solution of tasks on this subject, that are described in the Forest Management Program of the National park of Split Rock Lighthouse . Wisconsin, USA [36]. This Program includes measures aimed at both maintaining the existing carbon (protective actions) and increasing the ability of forests to capture carbon in the future (offensive actions). According to this Program, it is possible to focus on solving the following problems to ensure adaptive forestry: 1) preserving or increasing the area of forest lands and restoring forests after violations; 2) maintaining the fundamental ecological functions of the forest by supporting its species and structural diversity; 3) identifying areas with the highest carbon value in the landscape; 4) changing the species composition and structure of the forest to maximize carbon stocks.

The solution of the "adaptation and mitigation" problems at the third and final stage of geo-ecological monitoring of forests can based on the concept presented in [3] of carbon balances and functional stability of forest ecosystems in terms of global climate change. This concept reviews the related absorbing and adaptive capacity of forest biomes, mainly boreal, of European Russia in the conditions of the current global warming. The scientific search was conducted in accordance with the articles of the Paris Agreement on climate change [34]. The adsorption potential of native and derived boreal and nemoral forests of the Volga Basin was established, and their ability to mitigate climate change, including reducing anthropogenic warming, was assessed. A quantitative assessment of the loss of ecological resources by the forests of the region since the beginning of intensive forest and land use in it has been carried out.

As an integral assessment of the dynamic state of the "forest–climate" system, the well-known interpretation of the concept of ecological resources of forest cover was used [6, 12] as their ability to adsorb greenhouse gases using carbon cycle regulation mechanisms under climatic scenarios of regional warming and cooling. This regulation is aimed at returning the environment to the optimal state for the forest ecosystem and helps to maintain the relative stability of its production process in a changing climate, which also ensures the stability of the mechanisms of carbon cycle regulation itself as a leading link in the biological cycle. The obtained research results in this area can serve as an empirical substantiation of a new ecologically oriented paradigm in the doctrine of the forest [40].

It was given an account of comparative quantitative assessment of ecological resources in forest formations of the Volga River basin by specific and total values of their carbon balances under the predicted scenarios of climate changes. The ecological resources of two forest categories were assessed: primary and derivative. The main predictive climate scenarios were taken from E GISS Model [47], which gives the limits of climate changes corresponding to the purposes of the Paris Agreement [34].

According to this scenario, the maximum reduction of greenhouse gases in the atmosphere and consequently the maximally weakened regional warming are expected for two groups of primary forest formations – middle-taiga fir/spruce forests and middle and south taiga pine forests (Table 6, Figure 3): in each of them, the total carbon balance [$\sum \Delta C(Fa)$] approaches +190 million tons. The sub-taiga spruce and pine-broadleaf forests in the western sector of the basin have an almost equally high ecological resource, with [$\sum \Delta C(Fa)] \approx +140 \div 170$ million tons). The East-European broad-leaved forests are a striking contrast to the above-mentioned

Table 6 Total base carbon stocks, as well as total and specific carbon balances in restored primary (zonal-climax) forests Volga River basin (see Figure 6), according to the climate models of E GISS and HadCM3

Formation groups (see Table 1)	Total area spare, sq. km	The total base reser-ves of carbon, million tons	Total (specific) carbon balance, in million tons (t / ha), according to climatic scenarios	
			E GISS model, temporal thermo-arid trend, 2200	HadCM3 model, extremal thermo-arid trend, 2100
1	45927	508.596	+187.489 [+] (+42.45)	+91.205 [+] (+20.65)
2	128709	2368.889	–51.100 [–] (–4.14)	+2.222 [+] (+0.18)
3	96957	1975.984	+137.822 [+] (+14.82)	+103.785 [+] (+11.16)
4	32319	566.358	–26.800 [–] (–3.94)	+ 221.865 [+] (+32.62)
5, 6	65772	1246.708	+35.685 [+] (+13.78)	+40.372 [+] (+15.59)
7	93555	2445.425	+189.404 [+] (+21.14)	+147.563 [+] (+16.47)
8, 9	66339	1157.35	+173.537 [+] (+27.33)	+55.448 [+] +(9.05)
11	133245	2736.852	–102.622 [–] (–7.76)	+110.689 [+] +(8.37)
10,12	148554	2656.309	–56.891 [–] (–14.46)	– 13.613 [–] –(3.46)
13	8505	10.266	+2.416 [+] (+7.60)	+0.767 [+] +(2.41)
Swampy forests	5850	82.315	+7.172 [+] (+14.27)	+20.370 [+] +(40.53)
Forest swamps	2400	33.014	+5.798 [+] (+28.12)	+4.182 [+] +(20.28)
Nemoral floodplains	17361	255.762	+11.798 [+] (+7.91)	+12.469 [+] +(8.36)
Sum (average)	**845493**	**16043.828**	**+513.708** [+] **+(11.31)**	**+797.319 [+] +(14.02)**

Note: The [+] sign indicates the positive regulation of the carbon cycle under the given climatic trend, and the [-] sign indicates the negative regularity.

forest formations as they have a substantial negative effect on carbon exchange between the Earth's surface and the atmosphere: here $[\sum \Delta C(Fa)] > -100$ million tons. The negative balance in the marginal typical forest-steppe pine and broadleaf-pine forests increases more than twofold. On the whole, the process of climate-genic transformation of forest formations in the Volga basin, even according to the moderate thermoarid trend of the e-Hiss model, leads to a general decrease in the effectiveness of positive biotic regulation of the carbon cycle. This applies to both restored primary forests and real forest cover. In other words, global warming should lead to the inevitable loss by both bioclimatic systems of the basin (potential and real) of ecological resources in mitigating climate fluctuations. (see in Figure 3)

It is no less important to assess carbon cycle regulation by forest ecosystems at an extreme thermo-arid signal, according to the HadCM3 model [48], the climatic scenarios of which can be quite real if the current warming trend continues. According this model, the forest cover of the Volga River basin can acquire a mostly positive carbon balance under extreme warming (see Table 6; Figure 4). The East-European broad-leaved forests are already not a source of carbon, as they used to be at a weak thermo-arid signal, but it's sink. Together with boreal (sub-taiga and taiga) forests, they are capable of general positive regulation of the carbon cycle. Generally, we can state the *total mitigating effect of forest cover of the basin on climate changes as the hydrothermal signal becomes more intensive.*

It is planned to carry out a similar analysis with the forest communities of "Russian Forest" system at the topological and regional levels, with extrapolation of the results obtained to the forest cover of the entire Oka river basin. It is necessary to make a detailed assessment of the relative contribution of each group of biogeocoenoses and each regional type of forest formations to the process of atmospheric carbon adsorption, with account of their functional stability and the extent area in local and regional model territories. Those forest communities that have the maximum ability to adapt and mitigate and, thus, can contribute to the ecological safety of the environment in a changing climate in accordance with the well-known Le Chatelier's principle, according to [12] will be outlined. Such biogeocoenoses and forest formations are considered as priority communities in the selection of the most optimal assortment of tree species in various zonal, geomorphological and edaphic conditions. It will be a decisive step in achieving the final goal – unlocking of the ecological potential of forests, ensuring the transition to adaptive forestry. "Creating forests with high carbon-adsorbing potential ..." [12] is one of the strategic goals of adaptive forestry. This is especially important for afforestation in currently deforested areas in terms of expected climate changes, as well as for reforestation after fires and afforestation after logging.

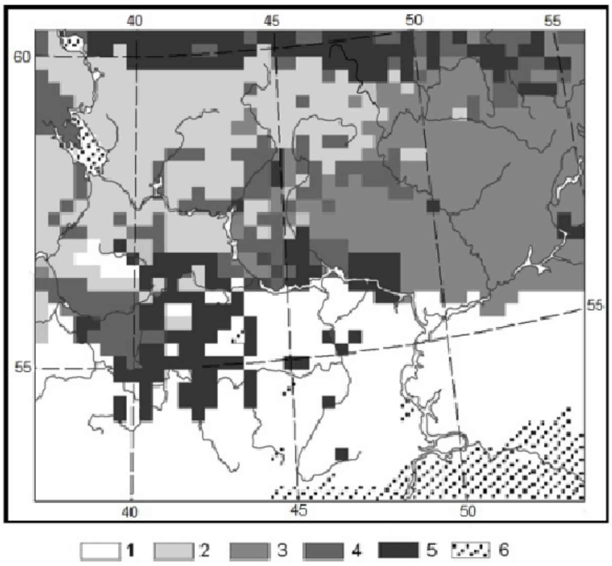

Figure 3 The distribution of the specific carbon balance in the restored primary forest formations of the Volga River basin for scenario of regional warming (2200), according to the E GISS model. Raster maps were calculated and compiled by L.S. Sharaya. Carbon balance (t / ha): 1 – (–15.0) ÷ (–7.5); 2 – (–7.5) ÷ 0; 3 – 0 ÷ 15.0; 4 – 15.0 ÷ 25.0; 5 – 25.0 ÷ 43.0. 6 – lakes, reservoirs and areas without forest vegetation.

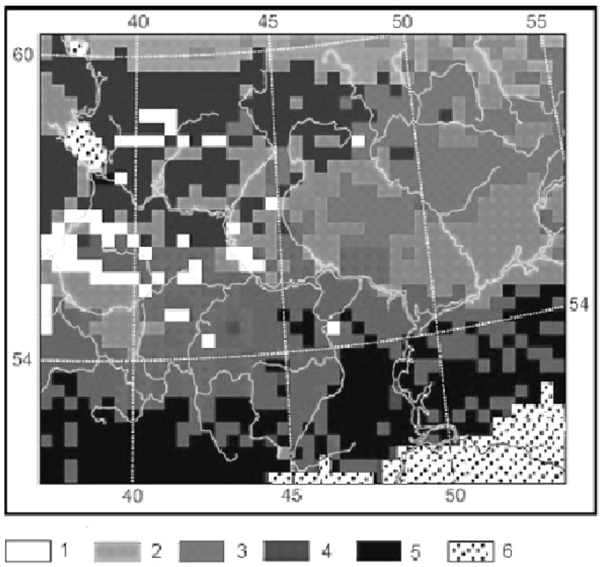

Figure 4 The distribution of the specific carbon balance (t / ha) of the restored primary forest formations of the Volga River basin for the extreme warming scenario, according to the HadCM3 model for a period of 2100. The raster map was calculated and compiled by L. S. Sharaya. Carbon balance (t / ha): 1 – 32.0–28.0; 2 – 27.9–17.0; 3 – 16.9–8.0; 4 – 7.9–3.0; 5 – 2.9 ÷ (–3.5). 6 – lakes, reservoirs and areas without forest vegetation.

When solving the problems of reforestation and afforestation, virtual predictive mapping of the carbon balance of forest formations can be of constructive importance [3]. We are talking about the construction of regression maps of the carbon balance of forest formations in the Oka river basin. The maps were be created on the basis of the identified statistical relationships between the carbon balance of various forest formations in the basin and the most significant environmental factors. Such maps will make it possible to more clearly present the partial contribution of various forest communities (both indigenous and derived) to the positive biotic regulation of the carbon cycle and to the corresponding provision of their sustainable development in a changing climate in areas with different zonal-climatic, geomorphological, and edaphic conditions.

6 Conclusion

The ultimate scientific-practical goal of the monitoring of the mechanisms of sus-tainable development of forest ecosystems in a changing climate, set out in this report, is to create theoretical, methodological and factual prerequisites for unlocking the ecological potential of forests, which can ensure the transition to adaptive forestry. Geo-system monitoring of forests may pave the way also to the understanding of the mechanisms of sustainable development of forest ecosystems in a changing climate and to the creation of scientific and methodological factors in order to implement mitigation of the current global warming by forestry methods. It has the general scientific and practical significance for the expected results of the research by given direction of the geographical ecology.

The stated strategy of scientific research assumes a periodically return sequence of the elements of the triad of geo-system monitoring “observation–forecast–management”, with the construction of empirical and statistical models of the transition of ecosystems “from the past to the future” at each step of the climate trend. The climate-genic component is picked out from the general series of the past dynamics of forest biogeosystems and then a forecast of their upcoming changes is given according to the further expected hydrothermal trend, taking into account the upcoming age and syn-genetic functional shifts in each biogeo-system group of forests. Simultaneous identification of environmental effects of the carbon balance of forest ecosystems in mitigation global warming is conducted. It is planned to carry out numerical experiments with hydro-thermal niches of forest biogeocoenoses according to climatic trends of the past and future. The working tool of the analysis is a kind of *sliding (pendulum) operating system*, where observation and forecast are repeated repeatedly – in accordance with the environmental results obtained for the previous period of climate change and with new hydrothermal signals that are expected in the future.

Conflicts of interest

The author declares there is no conflict of interest.

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