Role of Forests of the Volga River Basin in the Mitigation of Climate Fluctuations and of Forthcoming global Warming (Predictive Empirical-Statistical Modeling)

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Abstract. In this article, the authors propose a predictive landscape-ecological analysis of the forest cover of the Volga basin, which highlights the problem of adsorption of greenhouse gases, which is included in the list of tasks set the Paris Climate Change Agreement (2015). As a result of the study, the authors established the adsorption potential of indigenous and derived boreal and nemoral forests, assessed their ability to mitigate climate change, including reducing anthropogenic warming. A quantitative assessment was also made of the loss of these ecological resources by the forests of the Volga basin since the beginning of intensive forest and land use in it. We have identified contrasting changes in the ecological resources of boreal and nemoral forests during their structural transformation in the course of global warming. We show that the process of thermal-arid transformation of forest ecosystems leads to a general decrease in the positive carbon balance in most groups of forest formations. The verification of the predicted calculations of the carbon balance, carried out by remote and ground measurements in the boreal forests of Central Canada in the first decade of modern warming, gave positive results.

1. Introduction
The problem of the interaction of terrestrial ecosystems and the climate system through the carbon cycle, with the assessment of the greenhouse effect of the atmosphere, has already been covered quite widely both in domestic and foreign literature [1–5]. Up to now, the main attention is paid to the development of a method for determining carbon pools in various components of phytobiota and in soil, as well as to the creation of a database on the current carbon content in forest, bog and other ecosystems. For example, in [6], a method is described for compiling a hybrid map for Russia using satellite and ground data, including both land cover classes and some dominant tree species. On this basis, and using ground-based measurements of organic carbon stocks in the 0–100 cm soil layer, a map of carbon stocks for Russia with a resolution of 1 km was constructed. Using satellite laser scanning and auxiliary data, regional maps of the above-ground carbon stock were constructed in Central Siberia [7].

Significant progress has been made in studying the response of the global carbon cycle to changes in the climate system. A picture is given of the general patterns of the global carbon cycle and the greenhouse effect of the atmosphere in the Holocene and in the modern period in connection with temperature changes [8]. It was also possible to construct a forecast of the global carbon content in the
Global predictive estimates of the role of forest cover in the regulation of the greenhouse effect of the atmosphere are presented in small-scale scenarios of the carbon budget of the circumpolar boreal forests of Eurasia and North America based on the correlations of their biomes with climatic areas of temperature and precipitation [10, 11]. The expected impacts of climate change on Russian forests and mechanisms for forest adaptation are considered here to use the latter as a means of mitigating climate signals, which is included in the concept of transition to sustainable forest management in Russia. Given concept is still, as the authors themselves write, the character of "theoretical and methodological premises."

All these prognostic developments are small-scale and, hence, cannot reveal basic mechanisms accounting for the spatial diversity of the responses of forest communities to the same background climatic factors; in addition, the behavior of local ecosystems under conditions of climatic changes has been poorly studied.

Our report outlines the experience further development of the well-known concept of biotic regulation of the carbon cycle in the biosphere by studying the local mechanisms of the small biological cycle, which ensures the stability of the natural environment in accordance with Le Chatelier's principle [12]. The landscape-ecological approach to modeling the functional parameters of local ecosystems is based on the biochorological concept [13] concerning the spatial organization of the matter and energy cycles by the living matter in biogeocoenoses as discrete, elementary structural units of the biosphere. “The material and energy cycles of biogeocoenoses are interconnected and form a giant cycle of the biosphere” (ibid., p. 90).

According to theoretical developments in this field [14], the biosphere is regarded as a statistical ensemble of biogeocoenoses (landscape facies) as biochorological units that weakly interact with one another but have a highly ordered internal organization (due to stabilizing selection). Each ecosystem at the level of facies or their groups is assigned specific functional characteristics related to the structure of local matter and energy fluxes. This approach permits the prediction of the behavioral patterns of forest communities under different geomorphological and edaphic conditions on the basis of comprehensive empirical data collected in the course of field studies, while retaining the statistical methods of their analysis. Therefore, the prognostic models of local geographic space may include the mechanisms of the biotic regulation of the carbon cycle, which is a new aspect of solving this problem. This makes it possible to find the origins of the mechanisms of the phytobiota effect on the carbon exchange between the earth surface and the atmosphere and to identify those mechanisms that ensure the resistance of geo(eco)systems to climatic changes [15].

The knowledge of large-scale biospheric processes is closely associated with solution of the problem of conservation and reproduction of forest resources over vast territories under the conditions of global climate change. Forest cover is one of the decisive factors of stability of the continental biosphere [16]. Forests cover more than 49% of the land area of Russia, which corresponds to 20% of the total area of forest cover on the planet [17].

The contemporary global warming caused by increasing emissions of greenhouse gases to the atmosphere is an accomplished fact. Climate prediction on the basis of scenarios of technogenic greenhouse gas emissions to the atmosphere suggests an increase in the mean global temperature of the Earth's surface within 1.4–5.8°C over the period from 1990 to 2100, which is 2–10 times above the magnitude of warming that occurred in the XX century [18]. In accordance with the Paris Climate Change Agreement 2015 [19], measures should be taken for the warming to be no more than 1.5–2°C by 2050 in order to avoid global ecological disaster. One of these measures is "to reach the balance between greenhouse gases emitted as a result of human activity and their absorption by seas and forests" (Clause 4 of the Paris Agreement). Thus, the Paris Agreement presupposes the necessity to assess the role of natural ecosystems in carbon cycle regulation and stabilization of the environment via the processes of greenhouse gas adsorption.
The ideological basis of our research into the above problem was the new aspects of environmentally oriented paradigm in the doctrine of forest put forward in the works [12, 20, 21]. In addition to the known provisions of this paradigm (for example, the water protection and sanitary protection role of forests), the new aspects contain conceptual propositions on the ecological resources of forest cover as its ability to adsorb greenhouse gases by the mechanisms of carbon cycle regulation under the conditions of climate change. This regulation is aimed at returning the environment to the state optimal for forest ecosystems and contributes to the maintenance of relative stability of its production under varying climate conditions, which provides stability of the mechanisms of carbon cycle regulation as the key element of the biological cycle. The task of "maintenance of … the reproductive capability of forests … to protect forest resources … at the local, national and global levels" is a component of the strategy of sustainable forest management [22, p. 14]. One of the most important trends of this strategy is to use forests for climate change mitigation [11] by the mechanisms of biotic regulation of the carbon cycle.

The boreal forests of Russia provide over 90% of the carbon sink of all the world's boreal forests [11]. The total area of relatively undisturbed forests of Russia that can perform the function of stabilizers and regulators of the environment to the maximum extent possible [20] is from 3.45 to 4.65 million km² according to various estimates, i.e., up to one third of all virgin forests in the world [21]. At the same time, almost half of them are boreal forests providing more than 90% of the carbon sink of all boreal forests worldwide [11]. In bioclimatic interpretation, these are the climax or related quasi-climax (coniferous, mixed and broad-leaved) forest communities representing the final stage of endocrogenetic (restorative) successions, according to [16]. The latter consist of a series of derivative (secondary) small-leaved formations – mostly birch and aspen forests. The final succession stage brings the structure and functions of forest communities into conformity with the given zonal-regional climate conditions. Forest biomass is stabilized, and the closed biological cycle is restored. In mature ecosystems, the carbon increase due to photosynthesis outpaces its losses for heterotrophic respiration, thereby increasing their productivity. The depots of live phytomass and phytodetritus maintain their stability, thereby stabilizing carbon deposit and blocking its emission [20]. Hence, the maximum efficiency of soil-biotic mechanisms of stabilization and regulation of the environment is provided. It suggests that the primary climax and related forest formations, in contrast to derivative formations, must have the maximum ecological resource. This hypothesis should be verified.

This report gives 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 EGISS [23] belonging to the family of general circulation models: AOGCMs [24]. This model gives the limits of climate changes corresponding to the purposes of the Paris (2015) Agreement (see above). In the boreal belt of the Volga River basin, a $-0.5\pm1.9^\circ$ decrease in the mean July temperature is expected by 2050, with an increase in the atmospheric humidity factor ($F_{hum}$) from 1.15–1.52 to 1.27–1.79 (humidization), and its increase by $0.5\pm0.7^\circ$ with a decrease in $F_{hum}$ from 1.00–1.36 (aridization) is expected in 2200. Both prediction periods were considered irrespective of their timing, i.e., they have been used as models to answer the "what if..." question, regardless of when a particular predicted climate scenario occurs. A similar approach is adopted in the retrospective forecast based on paleogeographic data.

However, the currently existing warming trend can lead to a $4^\circ$ increase in the mean global temperature by 2100 [5]. At the same time, regional warming over the territory of Russia can be about $6–11^\circ$ [11], which is adequate to the climate prediction by the known extreme model HadCM3, version A2 [25], with a decrease in $F_{hum}$ from 1.29–1.37 to 0.78–0.75 in the boreal belt, i.e., to the level of southern forest steppe [26]. The analytical and cartographic results of our landscape-ecological studies of the Volga River basin based on this climatic model describe a quite probable pattern of dramatic aridization of natural environment in this part of the East-European subcontinent over the next 100–200 years.
2. Methods of forecast analysis

2.1. General provisions

In solving the problem, a non-traditional landscape-ecological approach was applied, based on the scientific and methodological developments of the author on the theory and methods of geographical ecology [15, 26]. The main characteristic of this approach is that the phenomenon of biotic regulation is considered at the topological level in landscape terms, thereby allowing for diverse types of this regulation determined by the spatial distribution of biogeocenoses (landscape facies) under different zonal/regional conditions. This makes it possible to find the origins of the mechanisms of the phytobiota effect on the carbon exchange between the earth surface and the atmosphere and to identify those mechanisms that ensure the resistance of geo(eco)systems to climatic changes.

The landscape–ecological approach is based on the construction of discrete empirical statistical models of natural ecosystems, by [26]. In these models, the results of field observations are used as an empirical basis for modeling itself, rather than as reference data for testing results of calculations. This, (a) minimizes the effect of the subjective factor in developing the model; (b) provides a considerably higher spatial resolution than, e.g., simulation modeling; (c) gives empirical grounds for wider geographic generalizations.

2.2. Calculation of carbon balances of forest biogeocenoses for the conditions of warming and cooling

Next ecomass parameters (tons/ha) have been used for calculation of carbon balance: (1) skeletal tree-shrub phytomass, BS; (2) root mass, BR; (3) total verdure mass, BV; (4) forest litter mass, ML; (5) debris – dead skeletal mass (brushwood and dead-wood), WD; (6) humus mass in organic-mineral layers of the soil, HU. Live phytomasses were calculated by the general and regional tables of biological productivity of fully stocked (normal) stands [27] using the average age and the bonitet of each species – the initial parameters obtained by forest taxation on test plots. The WD, ML and HU parameters were obtained empirically. The transition from ecomasses to their carbon content was performed using the known carbon coefficients [1, 21, 26, etc].

The thermo- and hydro-edaphic ordination of metabolic characteristics of topoecosystems was made by two geophysical parameters: the temperature of soil 50 cm deep and summer productive moisture reserves in the 0–50 soil layer. This parameter is most closely connected with atmospheric humidification. The functional characteristics of forest ecosystems also show the highest correlation with these parameters.

Calculation formulas are presented in the work (see [28], table 1). Correlation relationships are not always high enough (the coefficient of determination $R^2$ varies from 0.25–0.30 to 0.65–0.70), although they are quite significant (Pearson’s criterion $P = 1.0–2.5 \times 10^{-4}$). When describing complex multi-component biological systems, the correlation and determination coefficients cannot be high, since the regression equation most often describes the connections of the object under consideration with environmental conditions, and the biological system and its components exist according to their own internal laws [29]. Under the weak relationship, the latter can be interpreted only as a certain general tendency of changes of the given metabolic parameter under the influence of geophysical trend on the background of significant “noise” effect of other factors of the local order. The local scatter of metabolic characteristics caused by information "noise" was largely eliminated by the zonal-regional generalization of the results of topological ordering (see below).

For estimating changes in the carbon contents of individual biotic components and forest biogeocenoses in general, we used the traditional forest management method [30] which gives the best results at balance assessments of the carbon cycle components for long periods of time. Using discrete indicators of the small biological cycle, the change $\Delta C(Fa)$ in the mass of the carbon flux in the soil – plant – atmosphere system can be represented as follows:

$$\Delta C(Fa) = \Delta C(WD) + \Delta C(ML) + \Delta C(HU) - \Delta C(BS) - \Delta C(BV) - \Delta C(BR)$$
Here are the carbon pools corresponding to the above mentioned ecomasses. This balance equation was used to calculate possible changes of carbon flows between soil-plant cover and atmosphere in different periods of prediction (by E GISS and HadCM3) for each facies group in all eight regional ecosystems (see [26], paragraph 3.3).

Each member of the right part of the equation may have both positive and negative values. At positive values, the first three items give an increase of CO\textsubscript{2} emission from soil-plant cover into atmosphere and the other three give a decrease of this flow. In the latter case, the dead mass pool acts as an additional carbon source, while the live phytomass plays the role of its sink (deposit). With negative values of the above parameters, the picture is quite the opposite: in the reduced branch of biological turnover, carbon dioxide release into atmosphere decreases, while the autotrophic biogenesis becomes less intensive and consumes less CO\textsubscript{2}, thus compensating for the resulting deficiency of carbon dioxide in the atmosphere.

As a result, the total balance of changes of carbon exchange between biogeocoenoses and atmosphere $\Delta C(Fa)$ is formed, which must show whether this group of forest biogeocoenoses consumes additional amount of CO\textsubscript{2} from atmosphere due to the shifts in biological turnover induced by the global warming or, on the contrary, becomes a source of its additional emissions. In the former case, there is a negative feedback directed at realization of the Les Chatelier’s principle [12] for stabilization or even weakening of the primary thermo-arid climatic signal; in the latter case, there is a positive feedback, which leads to intensification of the greenhouse effect of atmosphere and, consequently, the warming itself.

Under cooling, the same components of the carbon balance have directly opposite effects as regards their contribution to cooling mitigation. At the negative and positive values of the sums ($\Delta C(BS)$ + $\Delta C(BV)$ + $\Delta C(BR)$) and ($\Delta C(ML)$ + $\Delta C(WD)$ + $\Delta C(HU)$), respectively, one can speak about positive biotic regulation of the cold climatic signal aimed at its weakening. Otherwise, this regulation will be negative, i.e., intensifying the process of cooling.

It should be emphasized that the values of the parameter $\Delta C(Fa)$ calculated according to equation (2) characterize the dynamic carbon balance of forest ecosystems caused by changes in the balance of the deposit and carbon emission in the soil and vegetation under the influence of a stable change in climatic conditions. This is, so to speak, the balance of balances – as the ratio of forecast balances to the balance of the end of the base period.

The initial objects of research were forest biogeocoenoses on 8 experimental grounds of the main catchment area of the Volga River basin (figure 1), where large-scale landscape-ecological surveys were made in 1987–1998 by the specially developed technique [26].

Among biogeocoenoses, there was a flat-interfluve (placor) group distinguished as a local zonal representative of this ecoregion. Other catena elements have been assigned to extrazonal topoecosystems characterizing different deviations from flat-interfluve biogeocoenoses under the influence of local geomorphological and edaphic factors refracting the given zonal-regional background. Extrazonal biogeocoenoses were considered as particular representatives of other natural zones and regions, often rather distant. Thus, the regional systems of local zonality were obtained for all experimental grounds [26]. The empirically revealed property of polyzonality of local ecosystems made it possible to extrapolate the results of large-scale landscape-ecological surveys (by 76 structural-functional parameters of biogeocoenoses) for almost the entire zonal range of the main catchment area of the Volga River basin: from middle taiga to northern steppe.
2.3. Calculation of carbon balances of forest formations

The transition from local level (scale 1: 50–100 000) to regional one (at the scales 1: 2–4 000 000) was carried out using the developed method of *inductive-hierarchical extrapolation*, which has been described in the work [15]. The method is based on the above-mentioned property of polyzonality of local ecosystems. The advantage of this method is that it uses directly the data of large-scale landscape-ecological surveys.

This procedure was performed using the vegetation maps for the European part of the former USSR at the above-mentioned scales compiled in the 70s-80s of the last century [31, 32], i.e., approximately at the time when we made large-scale landscape surveys. It was the time of termination of the basal period of 1885–1985, after which, as is known [24], the modern global warming began. The content of the maps was used as the initial factual material for basic and forecast ecological calculations, including the carbon balance of forest formations. According to [33], there are 13 classes (or groups) of indigenous plant formations on the territory of the Volga River basin (figure 1; table 1).

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**Figure 1.** Raster base map of zonal-provincial groups of primary vegetation formations (modern + restored) and the distribution of experimental test sites in the main drainage area of the Volga River basin. Experimental test sites (see [26]): 1 – Zhiguli; 2 – By-Sura; 3 – Green Town; 4 – Shchelokovsky Farmstead; 5 – Vyksa; 6 – Kerzhenets; 7 – By-Oka-Terrace Reserve; 8 – Kud’ma. For designations of groups of plant formations (1–13), see table 1. 14 – lakes and reservoirs.

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

| Zonal types and classes | Regional versions | Subzonal subtypes | Brief characteristics | Number and symbol |
|-------------------------|-------------------|-------------------|----------------------|-------------------|
| **A. Dark conifer and broad-leaf–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 |
| | | Middle and south taiga | Fir-spruce and spruce-fir grass-small shrub, with green mosses and grass | 4 |
| | Kama – Pechora – West Ural region | Sub-taiga | Fir-spruce complex nemorose-herbal | 5 |
| | | Broadleaf-fir–spruce nemorose-herbal | 6 |
| **B–C. 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 |
| | | Forest-steppe | Broadleaf-pine and pine complex, with spruce | 9 |
| | | and steppe | Pine and broadleaf-pine, with steppe undergrowth, and herbs-cereals | 10 |
| **D1. Broadleaf forest** | East European | Northern forest-steppe | Lime-oak and oak | 11a |
| | | | Lime with admixture of other broadleaf kinds | 11b |
| **D2. Typical and southern forest-steppe** | 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 newest Map of Forest Ecosystems of Northern Eurasia, compiled using satellite data from SPOT-Vegetation [17, 34], could not be used. The "types of vegetation" highlighted on it (for example, evergreen coniferous forests, deciduous coniferous forests, deciduous forests in general, mixed with a predominance of conifers, etc.) are of forestry rather than forest studies, which makes it difficult to interpret this map in light of the classical laws of forest biogeocoenology, according to [16]. Such forest categories do not at all correspond to the meaningful meaning of the concepts of "classes of plant formations" and "types of vegetation" [33] accepted in traditional geobotany, on the basis of which the classification of the vegetation cover of the Volga River basin was built.

Each group of formations includes forests communities of different ages (from young to overmature), which creates a certain diversity of carbon content in different pools. It is considered that the highest values of CO₂ deposit are typical of young and middle-aged plantations [17, 35]. However, the
influence of the forest age factor was avoided. While generalizing the data on each forest formation, we integrated the local geomorphological and hydro-thermoedaphic conditions of its formation, on the one hand, and eliminated the age-related contrasts between forest-forming species, on the other hand, which "erased" the respective spread in their productivity and made it possible to obtain certain values of both basal carbon content in different pools and its predicted carbon balance averaged for each group of formations. Thus, each forest formation was described by the averaged zonal-regional resources of carbon cycle regulation. These resources are composed of the topological diversity of the abiotic environment and the level of function of biogeocoenoses comprising this formation.

3. Modeling results and its discussion

3.1. Ecological resources of restored primary forests

First let us advert to the hypothetical (virtual) map of zonal-provincial groups of primary forest formations (see figure 1, table 1), where their modern areals are combined with the areas of secondary formations, as well as agricultural lands, found in their place according to cartographic data [32]. The map demonstrates the initial arrangement of the classes and groups of primary forest formations in the pre-industrial period, in the absence of intensive land and forest use. It represents the zonal-provincial phytoclimatic structure of territory of the Volga River basin. The basal total carbon content, the specific and total carbon balances of these hypothetical forests under changing climate conditions are presented in table 2. They inherently disclose the carbon cycle regulation by zonal-regional structure of the bioclimatic system of the Volga River basin for three mild (according to E GISS and HadCM3) scenarios of predicted climate changes: cooling and warming.

In general, the primary boreal and subboreal forests of the basin have two mutually opposite effects on the carbon balance between the Earth's surface and the atmosphere: (1) comparatively weak negative – under the cold-humid trend (additional CO₂ deposit and the respective intensification of cooling) and (2) much stronger positive (see table 2, bottom line) – under the thermo-arid trend (a threefold increase in ΔC(Fa)), which reduces the concentration of greenhouse gases in the atmosphere and thereby weakens anthropogenic warming. The total CO₂ adsorption from the atmosphere is about 1% of the total basal carbon content in boreal and sub-boreal forests in the former case and 3.5% in the latter case.

Let us consider in more detail the ecological resources of hypothetical forest cover of the Volga River basin for the scenario of regional moderate warming (see table 2). 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: in each of them, the total carbon balance (∑ΔC(Fa)) approaches +190 million tons. The subtaiga spruce and pine/broad-leaved forests in the western sector of the basin have an almost equally high ecological resource, with (∑ΔC(Fa)) ≈ +140÷170 million tons. The total carbon balance in the eastern sector (the Kama-Pechora-Western Ural) decreases almost four times (see table 2).

The East-European broad-leaved forests are a striking contrast to the above-mentioned forest formations as they have a substantial negative effect on carbon exchange between the Earth's surface and the atmosphere: here, (∑ΔC(Fa)) > –100 million tons. The negative balance in the marginal typical forest steppe pine and broad-leaved/pine forests increases more than twofold. Thus, the latter are not only have the lowest resistance to global warming [26] but even, as phytoecological systems with positive feedback, promote their own degradation by intensifying the given climatic trend. Unexpectedly, the values of total carbon balance proved to be negative in all south taiga fir-spruce forests.

The scenario of the cold-humid trend shows analogous ratios of absolute values (∑ΔC(Fa)) between the groups of primary forest formations; however, the sign of their carbon balance changes to the opposite: mainly positive carbon balance of primary forests contributes to further cooling.
Generally, the groups of primary forests of the Volga River basin, each of them filing its own zonal-regional ecological space, must have altogether positive and negative regulatory effects on the exchange of carbon between the terrestrial surface and the atmosphere under warming and cooling conditions, respectively; in the former case, it will be three times more intensive than in the latter case (see table 2, the bottom line). Due to rather high ecological resources, the primary boreal forests of the East-European subcontinent can be an efficient absorber of greenhouse gases from the atmosphere, thereby reducing the forthcoming global warming.

Table 2. The total basal carbon reserves, as well as the total and specific carbon balances, in restored primary (zonal-climax) forests of the Volga River basin (see figure 1) for the predicted periods up to cooling (2050) and warming (2100 and 2200), according to the EGISS and HadCM3 climate models

| Groups of formations (see Table 1) | Total area spare (km²) | Total base carbon stocks (million tons) | Total (specific) carbon balance, in million tons (t / ha), according to climatic scenarios |
|-----------------------------------|-----------------------|----------------------------------------|----------------------------------------------------------------------------------|
|                                   |                       |                                        | EGISS model                                                                     | HadCM3 model                                                                 |
|                                   |                       |                                        | cold-humid, 2050 r. | temporal thermo-arid, 2200 | extreme thermo-arid, 2100 |
| 1                                 | 45927                 | 508.596                                | –70.932 [+b] +187.489 [+] | +91.205 [+] (+20.65)      |
| 2                                 | 128709                | 2368.889                               | –122.565 [+] –51.100 [–] | +2.222 [+] (+0.18)        |
| 3                                 | 96957                 | 1975.984                               | +36.362 [–c] +137.822 [+] | +103.785 [+] (+11.16)     |
| 4                                 | 32319                 | 566.358                                | –64.274 [+] –26.800 [–] | +221.865 [+] (+32.62)     |
| 5, 6                              | 65772                 | 1246.708                               | +9.426 [–] +35.685 [+] | +40.372 [+] (+15.59)      |
| 7                                 | 93555                 | 2445.425                               | +111.725 [–] +189.404 [+] | +147.563 [+] (+16.47)     |
| 8, 9                              | 66339                 | 1157.35                                | +117.881 [–] +173.537 [+] | +55.448 [+] (+9.05)       |
| 11                                | 133245                | 2736.852                               | +18.118 [–] –102.622 [–] | +110.689 [+] (+8.37)      |
| 10, 12                           | 148554                | 2656.309                               | +58.859 [–] –56.891 [–] | –13.613 [–] (–3.46)      |
| 13                                | 8505                  | 10.266                                 | +4.165 [–] +2.416 [+]  | +0.767 [+] (+2.41)        |
| Swampy forests                    | 5850                  | 82.315                                 | +8.463 [–] +7.172 [+]  | +20.370 [+] (+40.53)      |
| Forest swamps                     | 2400                  | 33.014                                 | +2.142 [–] +5.798 [+]  | +4.182 [+] (+20.28)       |
| Nemoral floodplains               | 17361                 | 255.762                                | +0.223 [–] +11.798 [+] | +12.469 [+] (+8.36)       |
| Sum                               | 845493                | 16043.828                              | +109.586 [–] +513.708 [+] | +797.319 [+] (+14.02)     |

a The forested area for groups of formations 10 and 12 is taken equal to 26%, and for the 13th group of formations – 11%.

b the [+] sign indicates the positive regulation of the carbon cycle under the given climatic trend

c the [–] sign indicates the negative regulation of the carbon cycle under the given climatic trend
3.2. Anthropogenic changes in ecological resources of modern forest cover
What is the effect of anthropogenic changes in the boreal and subboreal forest cover of the Volga River basin that have taken place thus far on its ecological resources? What is the sign of these changes and what are the specific and total values of carbon balance? These issues are consonant with the global problem considered in the IPCC report (Vienna, 1998) "... the relationship of anthropogenic activity in the field of earth cover reconstruction with the distribution of CO2 and other greenhouse gases in the biosphere" [36, p. 211].

The basal and predicted carbon parameters were calculated for each of 13 groups of forest formations of the Volga River basin (see table 1), both for the restored primary forests and for the real forest cover including primary and derivative communities (table 3). The generally comparative pattern of carbon balances remains the same as described for the hypothetical forest cover of the basin. Under the thermo-arid scenario, the maximum specific ecological resources remain in the middle and south taiga and sub-taiga pine forests, as well as middle taiga fir/spruce forests, while the minimum resources are in the northern steppe broad-leaved forests and south taiga dark-coniferous communities. Total resources are determined also by the areas of forest formations; therefore, the general regulatory effect on the carbon cycle, e.g., of rarely occurring Kama and Western Pre-Ural coniferous/broad-leaved forests, as well as oak-lime forests of northern forest steppe, is insignificant.

Table 3. Specific carbon balances of the restored primary (zonal-climax) and real (primary + derivative) forest formations of the Volga River basin for the forecast periods of 2050 (cooling) and 2200 (warming). according to EGISS models

| Groups of formations (see table 1) | Specific base carbon content (t / ha) | Specific carbon balance (t / ha) |
|-----------------------------------|-------------------------------------|--------------------------------|
|                                   | Restored primary forests | Primary + derived forests | Restored primary forests | Restored primary forests | Restored primary forests | Restored primary forests |
| 1                                 | 110.74                  | 80.33                      | -16.06 [+]                | -11.64 [+]               | +42.45 [+]               | +30.78 [+]               |
| 2                                 | 184.05                  | 133.50                     | -9.93 [+]                 | -1.94 [+]                | -4.14 [-]                | -6.48 [-]                |
| 3                                 | 203.80                  | 233.58                     | +3.91 [-]                 | +0.68 [-]                | +14.82 [+]               | +16.45 [+]               |
| 4                                 | 175.24                  | 156.25                     | -9.45 [+]                 | -2.27 [+]                | -3.94 [-]                | -7.58 [-]                |
| 5, 6                              | 189.55                  | 169.27                     | +3.64 [-]                 | +0.49 [-]                | +13.78 [+]               | +11.92 [+]               |
| 7                                 | 154.50                  | 179.87                     | +12.47 [-]                | +10.89 [-]               | +21.14 [+]               | +10.21 [+]               |
| 8, 9                              | 174.46                  | 180.26                     | +18.57 [-]                | +8.94 [-]                | +27.33 [+]               | +16.39 [+]               |
| 11                                | 205.40                  | 182.65                     | +1.37 [-]                 | +5.83 [-]                | -7.76 [-]                | -5.82 [-]                |
| 10, 12                            | 178.81                  | 167.44                     | +14.96 [-]                | +13.50 [-]               | -14.46 [-]               | -12.73 [-]               |
| 13 Swampy forests                 | 15.12                   | +13.09 [-]                 | +7.60 [+]                 |                            |                            |                            |
| Forest swamps                     | 140.71                  | +16.84 [-]                 | +14.27 [+]                |                            |                            |                            |
| Nemoral floodplains               | 137.56                  | +10.39 [-]                 | +28.12 [+]                |                            |                            |                            |
| Average                           | **156.01**              | **148.89**                 | **+4.61 [-]**             | **5.00 [-]**             | **+11.32 [+]**           | **+8.54 [+]**            |

Specific carbon balances for separate groups of forest formations are within a range from 1–5 to 11–16 % of their specific basal carbon content. The exception is the sub-taiga broad-leaved/pine for-
ests and especially forest bogs, which absorb additionally up to 17 tons/ha and more than 28 tons/ha of carbon under warming conditions, respectively (see tables 2 and 3).

The comparison of specific and total carbon balances of the restored primary forests and the real forest cover (primary + derivative forests) show that the replacement of primary forests by derivative ones leads to the total and rather considerable decrease in the ecological resources of forest cover of the Volga River basin. It is manifested by the decrease in total positive regulation of the carbon cycle under warming conditions and by the increase in its negative regulation under cooling conditions (see tables 2 and 3, bottom lines). Distribution of birch and aspen forests in the middle and south taiga and in subtaiga pine forests, making a decisive contribution to the additional CO₂ absorption (under warming, more than 70% of the total volume of absorption), has particularly negative effects. Their average ∆C(Fa) values decrease almost twice under warming conditions: from 16.16 to 8.87 tons/ha. The ecological resource of the middle taiga fir/spruce forests also decreases by 27%, while the negative carbon balance in the south taiga East-European and Kama-Western Pre-Ural dark-coniferous forests increases by 40–50%. In the dark-coniferous south taiga and sub-taiga communities, as well as in the broad-leaved and steppificated pine/broad-leaved forests, secondary small-leaved formations have much less influence.

The wide distribution of restorative successions in the forest belt of the Volga River basin, with the predominance of long-derivative small-leaved communities, decreases the total additional absorption capacity of forests 2.8 times for the thermo-arid predictive scenario compared to the hypothetically restored primary forests. On the contrary, this capacity increases twofold under the cold-humid trend. In the former case, there is dramatic attenuation of positive regulation of the carbon cycle, while in the latter case there is slightly lesser but also significant intensification of negative regulation. Both cases provide direct evidence of reduced adsorption capacity of forest formations, with the presence of long-derivative formations together with primary communities. This is the general result of anthropogenic decrease in the ecological resources of forest cover of the Volga River basin since the beginning of intensive land and forest use in this region.

At a moderate thermo-arid signal, the carbon balance of forest formations is distributed rather distinctly. The middle and south taiga spruce forests and the birch forests replacing them over the entire northern and northeastern parts of the Volga River basin will reduce productivity (due to increased atmospheric humidification) and, accordingly, reduce the absorption of greenhouse gases from the atmosphere (∆C(Fa) will be −15÷30 to −45÷65 tons/ha); thereby, they must contribute to global warming. The weakly marked negative regulation of the carbon cycle (∆C(Fa) = −10÷35 tons/ha) should be expected from pine forests and lime forests of the forest steppe zone. At the same time, the primary broad-leaved/pine forests and their derivatives (birch and aspen forests) in the broad belt encompassing the subtaiga zone and the nemoral forest subzone will demonstrate rather marked positive regulation of the carbon cycle as they will increase their productivity, with the active absorption of CO₂ from the atmosphere (∆C(Fa) = 25–45 tons/ha; here and there, up to 60–85 tons/ha).

3.3. Ecological resources of forest formations under the conditions of extreme warming

It is no less important to assess carbon cycle regulation by forest ecosystems at an extreme thermo-arid signal, according to the HadCM3 model, the climatic scenarios of which can be, as it has already been said, quite real if the current warming trend continues. Compared to the E GISS scenario for 2200, this model gives an almost threefold increase in not only summer but also winter temperatures by the end of this century [26]. Accordingly, the length of the vegetation period must also increase, inevitably causing (together with the increased annual precipitation) an increase in productivity of forest communities with the respective intensification of greenhouse gas absorption.

As a result, the forest cover of the Volga River basin can acquire mostly positive carbon balance under extreme warming (see table 2, right column). For example, the East-European sub-taiga broad-leaf-spruce forests with weakly marked negative regulation of the carbon cycle (∆C(Fa) = −7.12 tons/ha) according to the E GISS warming scenario, become the subjects of substantial positive regulation (∆C(Fa) = +20.01 tons/ha) at a stronger thermo-arid signal according to the HadCM3 model.
The carbon balance of the Kama/Pechora/Western Ural primary sub-taiga forests changes similarly: from \(-18.24\) to \(+15.59\) tons/ha. In sub-taiga birch and aspen forests, positive regulation of the carbon cycle considerably increases \(\Delta C(F_a) = 8.37 \rightarrow 22.69\) tons/ha.

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 its 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.

Under the conditions of extreme warming (according to HadCM3), the difference in specific values of the carbon balance between restored primary and real forests is considerably smoothed out; however, with respect to the total balance, it remains equally significant (see table 2, the bottom line) or even increases for some zonal-regional groups of forest formations. It concerns first of all the East-European south taiga, where the restored primary forest cover shows positive regulation of the carbon cycle under extreme warming, whereas the mixed primary and derivative forests substantially increase its negative regulation. In sub-taiga broadleaf/dark-coniferous forests, the distribution of birch and aspen forests yields an opposite effect: an abnormal increase in positive carbon balance. It is especially marked in the Vyatka River basin and on the Vetluga-Vyatka interfluve.

3.4. Carbon balance of forest formations in the system of their thermo-arid transformations

The considered carbon balances of forest formations of the Volga River basin are the first approximation in the estimates of biotic regulation of the carbon cycle and describe only the starting response of forest communities to the given climatic signal in accordance with their original phytocoenological structure. However, the exposure to this signal is accompanied by functional and then structural adaptation of forest communities to new hydrothermal conditions. The mechanisms of this adaptation have been described in sufficient detail [26] as a system of probabilities and rates of landscape-ecological transitions. Obviously, transformation of a forest community of type A into a community of type B with certain probability must be accompanied by the respective changes in the biological cycle and carbon balance.

It was necessary to estimate with predictive calculations how is significant these connections, i.e. to carry out the second approximation in the estimates of the biotic regulation of the carbon cycle. It was necessary to calculate the changes in the carbon balance of forest communities during their functional and structural transformations within a certain predictive interval and thereby take into account the impact of adaptation mechanisms of forest communities on their carbon balances.

The solution of this problem makes it possible to obtain a second approximation in the estimates of biotic regulation of the carbon cycle, taking into account the effects of adaptation mechanisms of forest communities on their carbon balances. It precisely corresponds to the dual problem posed by the Paris Agreement 2015 [19], what includes: (1) identification of the absorbance potential of natural ecosystems, their ability to absorb CO\(_2\) from the atmosphere and thereby to prevent or reduce anthropogenic warming; (2) assessment of the adaptive possibilities of ecosystems under changing climate conditions, enabling them to perform absorption functions.

The second approximation was obtained by the example of the moderate thermo-arid trend for the period up to 2200 according to EGISS, using the model of probabilities of transitions between the groups of plant formations for the period of 2100–2150, according to GISS-93 [26]. Both models give generally similar shifts of the main climatic characteristics: the January and July temperatures, precipitation (annual, in the cold and warm periods), and the annual humidity factor. It is worth noting that, with regard to the temperature trend, these climate predictions fit into the limiting level of global warming in the XXI century, which is provided for by the Paris Agreement.

Table 4 presents the values of carbon balances of 13 considered groups of forest formations of the Volga River basin under the initial (basal) and final conditions within the prediction period up to 2200, according to EGISS. The final values are the average-weighted parameter \(\Delta C(F_a)\) calculated with the probability of stabilization of each group of formations and the probability of its transition into all other groups taken as weight coefficients. The carbon balances of the final state of forest formations char-
acterize their mechanisms of carbon cycle regulation already after the transformations that have occurred over the predicted period under the influence of the given thermo-arid signal.

Table 4. Specific carbon balances of the restored primary (zonal climax) and real (primary + derivative) forest formations of the Volga River basin in their initial and final states by the forecast period 2200 moderate warming according to the E GISS model

| Formation groups \[a\] | Specific carbon balance, t / ha | Restored primary formations | Real formations (primary + derivative) |
|-------------------------|---------------------------------|-----------------------------|--------------------------------------|
|                         | Initial state       | Final state   | Initial state       | Final state   |
| 1                       | 42.45 [+             | 19.01 [+       | 30.78 [+             | 10.98 [+       |
| 2                       | -4.14 [-             | 11.42 [+       | -6.48 [-             | 7.16 [+       |
| 3                       | 14.82 [+             | 3.74 [+        | 16.45 [+             | 4.00 [+       |
| 4                       | -3.94 [-             | 3.13 [+        | -7.58 [-             | 0.75 [+       |
| 5, 6                    | 13.78 [+             | 3.32 [+        | 11.92 [+             | -3.09 [-      |
| 7                       | 21.14 [+             | 9.74 [+        | 10.21 [+             | 4.21 [+       |
| 8, 9                    | 27.33 [+             | 4.29 [+        | 16.39 [+             | -0.14 [-      |
| 11                      | -7.76 [-             | -1.01 [-       | -5.82 [-             | -1.83 [-      |
| 10, 12                  | -14.46 [-            | 1.84 [+        | -12.73 [-            | -1.74 [-      |
| 13                      | -14.96 [-            | 4.79 [+        | -14.96 [-            | 4.79 [+       |
| Average                 | 7.43 [+             | 6.03 [+        | 3.82 [+             | 2.51 [+       |

\[a\] conventional meanings are as in tables 1 and 2.

In general, climatogenic transformation of forest formations of the Volga River basin, even according to the moderate thermo-arid trend of E GISS, leads to the total decrease in efficiency of positive biotic regulation of the carbon cycle. It concerns both the restored primary forests and the real forest cover. In other words, global warming must lead to inevitable losses of ecological resources by both bioclimatic systems of the basin (potential and real) in mitigation of climatic fluctuations, to a greater extent in the latter case compared to the former case (by 34% vs. 19%). At the same time, the twofold prevalence of potential over real resources (not taking into account the positive values of \(\Delta C(FA)\) in forest bogs, waterlogged forests and nemoral floodplains) is generally maintained.

Later on, climatogenic transformation of forest formations results in the general alignment of their original rather contrasting (from plus to minus) values of the \(\Delta C(FA)\) parameter: in formations with the negative starting carbon balance, it increases by the end of prediction period up to positive values; in formations with the high basal positive balance, it decreases (to zero and even negative values). As a result of temperature rise and decreasing annual humidity factor, sub-taiga boreal communities under the thermo-arid trend pass into the functional states of typical and even southern forest steppe by 40–50% [26], which leads to a decrease in their ecological resources by several times. On the other hand, the steppificated open oak and pine forests of typical forest steppe dramatically reduce their negative carbon balances as they acquire (by more than 40%) the functional properties of the entire series of more northern boreal forests – from middle taiga to sub-taiga. The broadleaf forests of northern forest steppe during their climatogenic transformation remain a source of \(CO_2\) emission to the atmosphere, though with a sevenfold decrease in this negative potential of carbon cycle regulation.
3.5. Verification of predictive calculations of the carbon balance

The described regularities of carbon cycle regulation by forests of the Volga River basin demonstrate rather high efficiency of using the actualistic method for numerical prediction of the ecological resources of forest cover. However, verification of computed prediction models is a highly difficult problem yet and the ways of its solution have not been found up to now. The main problem is that it is necessary to obtain a sufficiently long perennial series of direct (remote or field) measurements of the carbon content in numerous forest ecosystems, which represents the phytocoenological structure of a particular region. Such database has already started to be formed.

In this case, the analytical and cartographic data on carbon deposition/emission in forests of the boreal belt of Central Canada were used [3, 37]. Such data were obtained by repeated remote sensing over the period of 1990–2000 (note that it was the initial period of global warming), as well as terrestrial measurement and modeling for the Central plain part of Canada – the Saskatchewan and Manitoba provinces. This area of "Hudson taiga", with the predominance of high thick coniferous stands of Canadian spruce, American larch, balsam fir and Italian stone (black) pine. The widespread deciduous species are yellow birch, sugar (rock) maple, ash tree and beech. Forests are rather intensively cut down and suffer from fires and insect pests; nevertheless, beginning from 1990, the areas of managed Canadian forests remain relatively stable, while the average age of plantations is 92 years [3].

First of all, it was necessary to assess the comparability of the Volga River basin and the Central plain Canada with respect to regional climate predictions, as well as the carbon cycle parameters and the ecological consequences of forest management in predictive periods. These data are given in table 5. In general, both large ecoregions are quite similar with respect to major climatic trends. They describe an unambiguous increase in winter and summer temperatures (except for the abnormal cooling in the Volga River basin in 2050), as well as an increase in annual precipitation (except for temporal aridization of all Europe at the turn of the century).

| Deviations from base period a | Middle and Upper Volga Region | Central Canada |
|-----------------------------|-------------------------------|---------------|
|                             | 1990 | 1998 | 2050 | 1990 | 1998 | 2050 |
| \( t_{\text{Jan}} \)       | 0.8–1.4 | 1.1–1.6 | 1.6–2.1 | 0.1–0.7 | 1.4–1.9 | 1.6–2.1 |
| \( t_{\text{July}} \)      | 0.0–0.4 | 1.0–1.6 | −0.5÷(+0.1) | 0.1–0.4 | 0.3–0.8 | 0.7–1.1 |
| \( r_{\text{ann}} \)       | 110–292 | -(73÷292) | 73–328 | 73–292 | 36–256 | 73–328 |

*Average temperatures (°C): \( t_{\text{Jan}} \) – January. \( t_{\text{July}} \) – July. \( r_{\text{ann}} \) – annual precipitation (mm)

The modern carbon reserves in boreal forests of the Volga River basin are estimated to be 120–150 tons/ha. In forests of the plain central part of Canada, they are a little lower: 80–110 tons/ha. According to the data of predictive simulation model IMAGE2 [38], the carbon flow from terrestrial ecosystems to the atmosphere in both large ecoregions was no more than 0.15–0.20 tons/ha in 1990 due to deforestation, forest management and age-related dynamics of forest restoration after fires and logging but is supposed to increase to 0.20–0.50 tons/ha by 2050. It can be assumed that the Volga river basin and the Central Canada are and probably will remain under similar conditions of forest management, which makes it easier to compare them with respect to climatogenic dynamics of the carbon cycle.
Let us show the yearly and average changes in the ecosystem carbon sink ($\Delta \text{NEP(CO}_2\text{)}$, tons/ha·yr), as well as their total changes (in tons/ha) in the period of 1990–2000, in boreal forests of the Central Canada, according to [3]:

| Years | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|-------|------|------|------|------|------|------|------|------|------|------|------|
| $\Delta \text{NEP(CO}_2\text{)}$ | 0.113 | 0.083 | 0.135 | 0.057 | 0.061 | -0.170 | 0.061 | 0.104 | -0.096 | 0.017 | 0.087 |
| Average | 0.041 |
| Total | 0.452 |

Unfortunately, the period 2001–2009 turned out to be unrepresentative due to the massive destruction of the Hudson taiga by the actions of insect pests (bark beetles) and a sharp drop in forest productivity.

With the exception of reduced carbon sink in 1995 and 1998, when catastrophic forest fires spread over the Central Canada, the mean value of $\Delta \text{NEP(CO}_2\text{)}$ for this 11-year period was 0.080 tons/ha·yr. This value is close to our calculated data on the yearly carbon balance according to the extreme model HadCM3 – first of all, for the real forest cover of the Volga River basin (table 6). For the primary and real forests of the basin for the same period, according to the HadCM3 model, the $\Delta \text{NEP(CO}_2\text{)}$ values turned out to be 0.117 and 0.085 t/ha·year, respectively, which is very close to the “Canadian control”. Model E GISS gave clearly underestimated forecast results – 0.051 and 0.015 t/ha·year.

Thus, for the initial decades of global warming, the verification of our forecast calculations of the carbon balance yielded positive results only for the extreme model HadCM3. This indicates that modern global warming is characterized by such high rates of temperature rise that do not correspond to the above-mentioned rate set by the Paris (2015) Agreement on climate change [19]. Only ecological forecasts according to the E GISS model can be adequate to this norm, but their implementation provides for a sharp decrease in the adsorption potential of forests.

The linear extrapolation of the dynamics of carbon sink in Canadian forests will show the following total increase in their carbon reserves: about 0.40 tons/ha for the predicted period up to 2050, 0.80 and 1.60 tons/ha for the predicted periods up to 2100 and 2200, respectively. When comparing these values with our prediction data (see tables 2 and 3), we can see that they are lower by an order of magnitude. Obviously, it is impossible to verify our predictive calculations for the long-term future (after 2050) on the basis of factual data on Canadian forests in the interval of the first 10 years of global warming. Our calculation models of predicted changes in the carbon content in different pools of forests biogeocoenoses, according to the results of its basal hydrothermo-edaphic ordination, have the appearance of not only linear but also parabolic and exponential relationships (see [28], table 1), which gives the total ascending trend of the $\Delta C(Fa)$ parameter not confirmed by the linear trend of its changes based on the empirical data on the initial period of global warming.

The predicted temperature trend is of great significance per se. Almost all prediction models of the AOGCMs family describe an exponential but not linear increase in global temperature after 2000 [18, 39], which must initially predetermine the increasing trend of predicted positive carbon balance in the boreal forest cover.
Table 6. The specific carbon balances (tons/ha∙yr) of restored primary (zonal climax) and real (primary + derivative) forest formations of the Volga River basin for the predictive periods of global warming according to EGISS (2200) and HadCM3 (2100)

| Groups of formations (see Table 1) | E GISS model | HadCM3 model |
|-----------------------------------|--------------|--------------|
|                                   | Restored primary forests | Primary + derived forests | Restored primary forests | Primary + derived forests |
| 1                                 | 0.192        | 0.140        | 0.172        | 0.125        |
| 2                                 | – 0.019      | – 0.029      | 0.002        | – 0.086      |
| 3                                 | 0.067        | 0.075        | 0.093        | 0.199        |
| 4                                 | –0.018       | –0.034       | 0.272        | 0.091        |
| 5, 6                              | 0.063        | 0.054        | 0.130        | 0.128        |
| 7                                 | 0.096        | 0.046        | 0.137        | 0.071        |
| 8, 9                              | 0.124        | 0.074        | 0.075        | 0.074        |
| 11                                | –0.035       | –0.026       | 0.070        | 0.039        |
| 10, 12                            | –0.066       | –0.058       | –0.029       | –0.037       |
| Swampy forests                    | 0.035        |              |              | 0.020        |
| Forest swamps                     | 0.065        |              |              | 0.398        |
| Nemoral floodplains               | 0.128        |              |              | 0.169        |
| Average                           | **0.051**    | **0.015**    | **0.117**    | **0.085**    |

4. Conclusion

1. The experience of landscape-ecological analysis of the biotic regulation of the carbon cycle demonstrates the effectiveness of applying modern methods of biogeocenology to solving systemic problems of ecological forecasting, in particular, with the phenomenon of the forthcoming global warming. The main advantage of these methods is that they consider a system with feedback (negative or positive), which is often lacking in well-known methods of well-known simulation modeling. First, a variety of mechanisms for the mapping of global biospheric processes in the functioning and structure of ecosystems of topological dimension are revealed. Second, the directions and intensity of the reverse differentiated impact of forest phytobiota on the chemical composition and greenhouse effect of the atmosphere are established, with a corresponding assessment of environmental consequences.

2. 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. The generalized data on ecological resources of the boreal and nemoral forest cover of the European Russia and the Pre-Urals can be used for quantitative assessment of the effects of forests in these regions on the fluxes of greenhouse gases in the Earth surface–atmosphere system.

3. It is predicted that different forest associations and formations at the same climatic signal will both additionally absorb greenhouse gases (the positive carbon balance of forest communities) and emit them to the atmosphere (the negative balance), exerting the respective effects on the state of terrestrial ecosystems. Each ecoregion was shown to have particular zonal-regional types of regulation of
CO₂ content in the atmosphere by forest cover during the development of a thermo-arid or cold-humid trend.  

4. It has been proved empirically that the replacement of primary forests by derivative forests results in very significant reduction of ecological resources of the boreal forest cover. The mean values of positive specific balances there under warming (even according to the moderate climate model EGISS) decrease two–three times. This is the anthropogenic loss of ecological resources of boreal forests of the Volga River basin since the beginning of intensive land and forest use there.  

5. In the course of the influence of the climatic signal, a functional and then structural adaptation of forest communities to new hydrothermal conditions occurs, and this is accompanied by corresponding changes in their carbon balance. It has been shown that climatogenic transformation of forest ecosystems, even according to the moderate thermo-arid trend, results in the total reduction of positive carbon balance in most formations of boreal forests, whereas the initially negative balance of steppe- and insular forests in the sub-boreal belt increases to positive values. The stated experience of analytical modeling of changes in the carbon balances of forest formations of the Volga river basin in the system of their thermo-arid transformations, according to one of the global warming scenarios, sheds some light on the dual problem posed by the Paris Climate Change Agreement (2015) concerning the necessity of coupled analysis of the absorption capacity of forest biomes and their adaptation to the changing climate.  

The author does not pretend to be a comprehensive solution to the tasks set. One of the types of predictive ecological models is outlined – precisely within the framework of experimental geographic (landscape) ecology.  

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