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RESEARCH ARTICLE

Regulatory Roles of Boreal and Nemoral Forests in the Volga River Basin in Carbon Cycle and Anthropogenic Warming Mitigation: A Predictive Empirical-Statistical Modeling Study

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Abstract: The well-known conceptual provisions on the ecological resources of forest cover as their ability to additionally absorb greenhouse gases through the mechanisms of carbon cycle regulation under global climate change are empirically substantiated. A predictive landscape-ecological analysis of forest cover in the Volga River basin is presented, which highlights the task of greenhouse gas sequestration included in the list of tasks of the Paris Agreement (2015) on climate change. Data from large-scale landscape surveys previously conducted by the author in the Middle and Upper Volga regions were used. Calculations of the carbon balance of forest formations in the Volga River basin were performed for global moderate and extreme warming scenarios. Multiple regression methods were used to reveal the spatial variability of forest carbon balance in relation to changes in forest ecosystems' adaptive potential and the climate predicted for 2100 by the global HadCM3 model, which was consistent with the current unprecedented rate of global warming. The absorption potential of indigenous and derivative boreal and nemoral forests was established; their ability to mitigate the effects of climate change, including the reduction of anthropogenic warming, was assessed. Contrasting changes in the ecological resources of boreal and nemoral forests amid global warming were identified. A quantitative assessment of the loss of ecological resources of forests in the Volga River basin since the beginning of intensive forest and land utilization was conducted. Using the Volga River basin as an example, a regional experiment was conducted to numerically solve the dual problem set by the Paris (2015) Agreement on Climate Change: namely, to calculate the sequestration of CO_2 from the atmosphere by forest communities under current global warming, taking into account their adaptation to climate change.

Keywords: forest ecosystems, boreal belt, indigenous and derivative forests, climate change, carbonbalance, predictive empirical-statistical modeling

1 Introduction

The knowledge of large-scale biospheric processes is closely associated with the 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 [1,2]. Forests occupy more than 49% of the land area of Russia, which corresponds to 20% of the total area of the planet's forest cover [3].

The Earth's indigenous forests remain on an area of about 13.5 square kilometers (km^2), which is 40% of the land area. Of these, almost half of the area is boreal forests, of which more than 51% are indigenous forests in Russia [4]. For comparison, Canadian forests account for 10% of the world's total forest area and 20% of the sub-polar boreal forest biome [5]. The share of Russian forests reaches almost a third of all virgin forests in the world [6], and Russian forests provide over 90% of the carbon sink of all the world's boreal forests [7].

The forest cover, which passes atmospheric moisture through itself and increases its transpiration abruptly to the atmosphere, plays the role of a kind of pump that consistently pumps and spreads this moisture from the oceans to the continents, thereby ensuring the stability of the functioning of terrestrial biogeosystems [8,9], including their maximum possible productivity. This is the global mechanism of positive feedback between forest productivity and precipitation, which "... inevitably leads to ... the relative integrity of the structural parts of the biosphere" [10–12].

Based on the example of the forest cover of Finland, a study was carried out on the sensitivity of managed boreal forests to climate change, with the following assessment of the adaptation of forest management to climate change [11]. It was shown that climate change can significantly change the dynamics of managed boreal forests in northern Europe.

The contemporary global warming caused by increasing emissions of greenhouse gases into the atmosphere is an accomplished fact. Climate prediction based on scenarios of technogenic greenhouse gas emissions to the atmosphere suggests an increase in the mean global temperature of the Earth's surface by 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 20th century [12]. However, the real picture is much better than these calculations. The current warming trend will lead to an increase in the average global temperature by 4°C by 2100 [13]. At the same time, regional warming in the territory of Russia can be on the order of 6–11° [14].

In 2015 in Paris, during the Climate Conference under the United Nations Framework Convention on Climate Change, an Agreement was reached to regulate measures to reduce carbon dioxide in the atmosphere from 2020 onwards [15]. Following the Paris Climate Change Agreement, *measures should be taken to keep warming to be no more than* 1.5–2.0°C by 2050 *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 adsorption by seas and forests" (Clause 4 of the Paris Agreement).

This report, using the example of boreal and nemoral forests of the Volga River basin, describes the experience of predictive regional analysis of the resource potential of forest cover in absorbing greenhouse gases and correspondingly mitigating modern warming.

2 Scientific-methodological prerequisites for the study

The ideological basis of our research into the above problem was the new environmentally-oriented paradigm in the doctrine of forestry put forward in the works [6, 16, 17]. The paradigm contains 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 their production under variable climate conditions, which provides stability of the mechanisms of carbon cycle regulation as the key element of the biological cycle. These are the major ecological biosphere-stabilizing functions of forest [17], *i.e.*, the leading "ecosystem services" of forest cover [18]. The task of "maintenance of ... the reproductive capability of forests ... to protect forest resources ... at the local, national and global levels" was a component of the *strategy of sustainable forest management* [7, 14]. This is essentially about the need to switch to adaptive forestry, taking into account the special sensitivity of forests to "rapid" climate changes, to ensure the adaptation of forests to global changes and their use to mitigate unwanted climate changes [19].

The total area of relatively undisturbed forests of Russia that can perform the functions of stabilizers and regulators of the environment to the maximum extent possible [16, 17] is from 3.45 to 4.65 million km^2 according to various estimates, *i.e.*, up to one third of all virgin forests in the world [6]. At the same time, almost half of them are boreal forests providing more than 90% of the carbon sink of all boreal forests worldwide [7]. In bioclimatic interpretation, these are the climax or related quasi-climax (coniferous. mixed and broad-leaved) forest communities representing the final stage of endo-eco-genetic (restorative) successions, according to Gribova et al. [20]. 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 from heterotrophic respiration, thereby increasing their productivity. The pools of live phytomass and phytodetritus maintain their stability, thereby stabilizing carbon deposit and blocking its emission [17]. 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.*

3 Source materials

The source analytical and cartographic materials for forecast analysis were vegetation maps of European Russia [21, 22] at scales of scales 1: 2–2.5,000,000, as well as the results of our large-scale (scale 1: 25–50,000) landscape surveys by a specially elaborated method in the forest zone of the Volga River basin, at eight experimental test sites [23]. The surveys were carried out in the same years (1987–1998) when these maps were created. Note that, according to climate forecasts, this was the end of the base period 1885–1986, after which, as was known [24], modern global warming began.

The test sites embrace a wide range of zonal plant formations – from south forest-steppe to mixed forests (Figure 1). Each of these test sites is representative of a particular *regional ecosystem*, with its corresponding conventional name: 1 – Zhiguli, 2 – By-Sura, 3 – Green Town, 4 – Shchelokovsky Farmstead, 5 – Vyksa, 6 – Kerzhenets, 7 – Kud'ma, and 8 – By-Oka-Terrace reserve (BOTR).

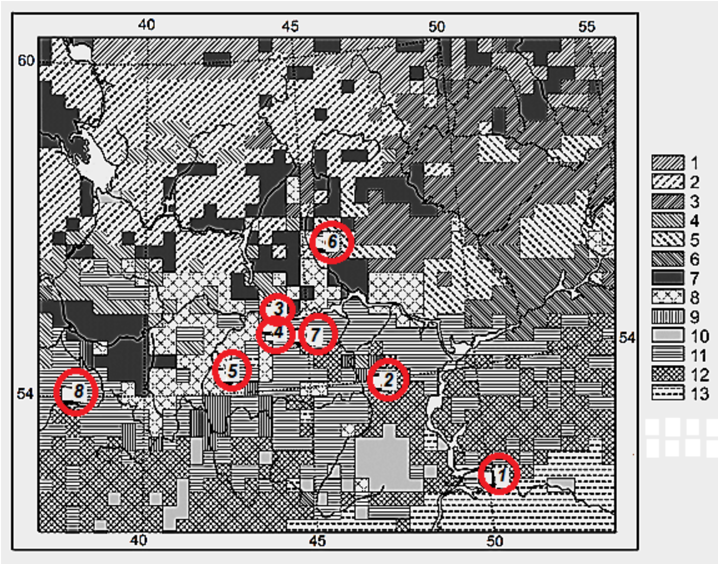

Figure 1 Raster base map of zonal-provincial groups of indigenous plant formations (modern + restored) on the territory of the main drainage basin of the Volga River basin. The map is designed and compiled by author with the participation of L.S. Sharaya. 1÷8 – numbers of experimental polygons (see in the text).

The local geoecological space of each ecoregion is characterized by a certain set of phytocoenoses and soil differences, their distribution by micro-relief forms, and respective hydrothermal regimes. *The landscape facie*, by Klijn and Udo [25], or *biogeocoenosis*, by Sukachev [2], is main local (topological) operational unit in our researches. This elementary unit of geographical ecology accepted in Russia corresponds to categories "Site", "Ecoelement", and "Landtype Phase" in the classifications of Australia-Britain, Canada, and the USA, respectively [26].

Figure 1 shows the locations of 8 experimental sites. Each test site included 40–50 sample areas (forest biogeocoenoses), which together characterized this regional ecosystem. When modeling, the high emphasis was placed on the phytocoenotic functional block – the parameters of annual and perennial cycles of plant matter turnover which are especially important for prognostic ecological investigation. Such turnovers are the most important indicators of ecosystem resistance to external disturbance [27]. The following phytomass parameters (tons/ha) were 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 phytomass was calculated from the general and regional tables of biological productivity of fully stocked (normal) stands [28] using the average age and the quality of locality 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 phytomass to its carbon content was performed using the known carbon coefficients.

The transition from local to regional levels (at the scales 1:2–1:4,000,000) was carried out using the method developed in this study of *inductive-hierarchical extrapolation*. The method is based on the above-mentioned *property of polyzonality of local ecosystems* [23]. The advantage of this method is that it uses directly the data of large-scale landscape-ecological surveys.

The cartographic materials we used [21, 22] have not lost their relevance to the present day. It was established [3] that during the period from 1968 to 2008, the forest cover of the European part of Russia changed by only 6–8%. The species structure of forests also changed insignificantly: the share of coniferous species decreased by 4%, and the share of soft-leaved trees increased by 5%, which meant a slight "... decrease in the share of indigenous, economically valuable coniferous and hard-leaved species" ([3], p. 39). The ratio of areas with different age structure of forests also changed slightly.

The newest map of Forest Ecosystems of Northern Eurasia, compiled using satellite data from SPOT-Vegetation [3, 4], 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 Sukachev [2]. Such forest categories do not at all correspond to the meaning of the concepts of "classes of plant formations" and "types of vegetation" [29] accepted in traditional geobotany.

According to Gribova et al. [20], the main representatives of natural zones and sub-zones are primary plant formations, the classification scheme of which for the territory of the East European Plain is given in Table 1. Phytocenological units of small-scale geobotanical maps belong to classes (and sub-classes) of plant formations (PF), which are regional variants of vegetation types and subtypes [29].

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

Plant formations, by Kotova [21]			Groups of plant associations	
Zonal types and classes	Regional versions	Sub-zonal sub-types	Brief characteristics	Number and symbol
Dark conifer and broadleaf– dark conifer forests (secondary aspen –birch)	East European (Upper Volga region)	Middle taiga	Spruce green mosses with small shrubs	1
		South taiga	Spruce smallshrub-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-smallshrub, with green mosses, and grass	4
		Sub-taiga	Fir-spruce complex nemorose-herbal	5
			Broadleaf–fir–spruce nemorose–herbal	6
Pine and broadleaf–pine forests (secondary aspen –birch)	East European (Upper Volga Region)	Middle and south taiga	Pine, with spruce, green mosses with smallshrubs	7
		Sub-taiga	Pine (with oak in under-growth) smallshrub-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	116
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

In Figure 1, a basic raster map of zonal-provincial groups of plant formations of the Volga River basin is presented in scale 1: 8,000,000. The habitats of each of the phytocoenological groups included indigenous forest communities (dark and light coniferous, mixed, broad-leaved) – both modern and restored instead of long-term derivative (small-leaved) forests, as well as agricultural landscape complexes. The ranges of each phytocoenological group included indigenous forest communities (dark and light coniferous, mixed and broadleaf) – 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 have be given, which is very important for comparison with the predicted carbon balance of real forests. It has also been shown how the regulatory role of the boreal and nemoral forests of the Volga River basin in the carbon exchange between the earth's surface and the atmosphere has changed as a result of their centuriesold anthropogenic transformation and generally deforestation.

The main catchment of the Volga River basin includes a vast territory with extreme anthropogenic transformation, where a single space has formed with almost completely disturbed forest cover. A typical example of such a space is the Oka River basin, where forest and water resources were depleted, with a loss of phytomass of more than 50%, with the loss of the gene pool and unique natural objects [6].

4 Methods of research

It was necessary to establish the local mechanisms of biotic regulation of the carbon cycle and the regional patterns of this regulation based on predicted changes in discrete parameters of the small biological cycle in forest biogeocoenoses under the specified variants of climate prediction for a particular period. The potential of biotic regulation of the carbon cycle was assessed using the hydrothermal ordination of discrete metabolic parameters of forest ecosystems under different zonal-regional and local conditions of the Volga River basin.

The thermo- and hydro-edaphic ordination of metabolic characteristics of topo-ecosystems was conducted based on two geophysical parameters: the temperature of soil 50 cm deep *(*t_{50}*)* and summer productive moisture reserves in the 0–50 cm soil layer *(W-50)*. These parameters are most closely connected with atmospheric humidification. The functional characteristics of forest ecosystems also show the highest correlation with these parameters. However, this signal must be constantly acting and unidirectional, and this is its effectiveness. Correlation are not always rather high but quite significant (Pearson's test of significance, $P \ll 0.05$). The R^2 values ranged from 65–75% to 25–35% (Figure 2). In cases of weak correlation, the latter can be interpreted only as a certain general tendency of changes of the given metabolic parameter under the influence of the geophysical trend against the background of significant "noise" effect of other factors from the local order.

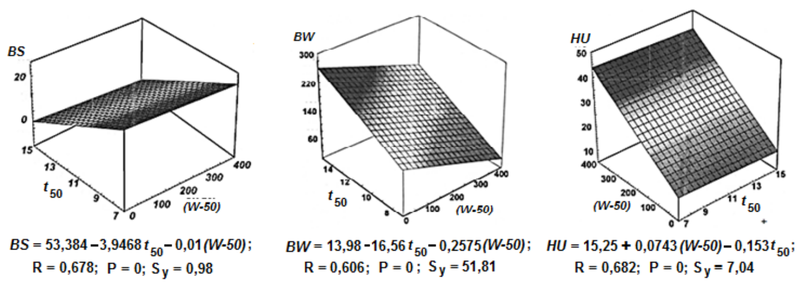

Figure 2 Linear distribution surface of biological cycle parameters in space of soil hydrothermal factors on the mixed forests of the boreal-nemoral forest ecotone, regional ecosystem "Green Town", experimental test site 5 (see in the Figure 1).

As is known [30], violations of the basic principles of statistical analysis were inevitable when describing complex multicomponent biological systems. In particular, the principle of linear independence of predictors was not observed, and the correlation and determination coefficients could not be high. Asymmetrization and fragmentation of hydrothermal niches, with a predominantly Poissonian distribution of biogeocoenotic units, indicate a complex process of their climate-induced transformations differentiated in space [23]. The main task of the ordination research is to separate the signal under study from "noise" (and not to achieve unambiguous connections) and to quantify the magnitude of this signal.

To estimate changes in the carbon contents of individual biotic components and forest biogeocoenoses in general, we used the traditional forest management method [1] based on the estimation of the dynamics of live phytomass and necromass (and the humus mass), which yielded the best results in CO_2 balance calculations over long periods. Using the considered discrete parameters of the minor biological cycle (see above), the change in the mass of carbon flow $\Delta C(Fa)$ in the soil–plant–atmosphere system could be represented in the following form:

$$\Delta C(Fa) = \Delta C(WD) + \Delta C(ML) + \Delta C(HU) - \Delta C(BS) - \Delta C(BV) - \Delta C(BR) \quad (1)$$

This balance equation was used to calculate possible changes in carbon flows between soil-plant cover and the atmosphere in different periods of prediction for each facies group in all regional ecosystems. The values of some of these coefficients (e.g., *BV, ML*, and *HU*) were differentiated by each experimental test site and by each of the facies group on a test site depending on the zonal and local habitat conditions.

The total balance of changes in carbon exchange between biogeocoenoses and the atmosphere $\Delta C(Fa)$ was formed, which would show whether this group of forest biogeocoenoses consumes the additional amount of CO_2 from the atmosphere due to the shifts in biological turnover induced by the global warming or, on the contrary, became a source of its additional emissions. In the former case, there was negative feedback directed at the realization of Les Chatelier's principle for the stabilization or even weakening of the primary thermo-arid climatic signal; in the latter case, there is positive feedback, which leads to the intensification of the atmospheric greenhouse effect and, consequently, the warming itself.

It should be emphasized that the values of the parameter $\Delta C(Fa)$ characterize *the dynamic carbon balance of forest ecosystems* due to changes in *the balance between carbon deposition and emission in the soil and vegetation cover* under the influence of a stable change in climatic conditions. This is, so to speak, the balance of balances – like the ratio of forecast balances to the balance of the end of the base period. The dynamic balance was fundamentally different from the traditional static carbon balance, which was calculated for given soil-geomorphological and phytocoenotic conditions under a stationary climate.

The maps of the basic and predicted metabolic parameters based on statistically significant relationships between the functional characteristics of the ecosystems and the terrain (see Figure 2) allowed the changes in the metabolic parameters to be quantitatively estimated while accounting for their spatial differentiation and relative contributions of the main forest associations and formations of the southern forest zone to the changes in the carbon cycle. To map the initial (basic) carbon content of different pools of forest biogeocoenoses in a given ecoregion, we used NASA satellite data on the terrain, namely, digital elevation models (DEMs) of the Earth's surface with a resolution of 90 m obtained in the course of the international (United States–Italy–Germany) Shuttle Radar Topography Mission (SRTM) implemented in 2000 (http://e0dps01u.ecs.nasa.gov/srtm/).

5 Results and discussion

The regional scenario of anthropogenic climatic changes in the ongoing century was taken from two global prognostic models of the atmosphere-ocean coupled general circulation models (AOGCMs): 1) moderate global prognostic climatic E GISS model [31], and 2) extreme HadCM3 model, Version A2 [32]. The first model gave limits on climate change that corresponded to the goals of the Paris Agreement (2015) [15] – to prevent average annual warming to more than 1.5–2.0°C by the middle of this century, *i.e.* to the date of the doubling of CO_2 concentration in the atmosphere. According to the extreme HadCM3 model, the increase in July temperatures in the Middle Volga region would be 2–3°C by 2050, and at the end of the 21st century it would reach 5.5–7.0°C. The annual precipitation amount would change slightly. According to this thermo-arid scenario, the entire south of the boreal zone on the Russian Plain would be in sub-boreal climatic conditions. The latter could already exceed the endurance threshold of the main forest-forming species and cause the disintegration of not only nemoral, but also boreal forests over vast areas. It should be noted that the climate forecast according to the HadCM3 model [32] was consistent with the current warming trend (see above). We considered all forecast periods regardless of their timing, *i.e.* they were used as models to answer the question "what will happen if...".

The local mechanisms of biotic regulation of the carbon cycle were investigated based on predicted changes in the biological cycle of forest biogeocoenoses under climate change scenarios projected to 2150 (Table 2). The main results of empirical-statistical prediction are presented below:

(1) The decomposition part of the biological cycle was the most sensitive to climatic impacts; nevertheless, over sufficiently long periods *the maximal (by absolute values) changes occur not in this branch but in autotrophic biogenesis: the general net production of forest communities.* Moreover, skeletal tree-shrub phytomass (*BS*), mainly wood gain, accounts for the largest part of the shifts of productivity and carbon content. Such a regularity was identified in both climate prediction models and is typical of all considered forest ecosystems (Tables 2 and 3). In 2100, the changes in total carbon content at their extreme values would range from –(78–100)

tons/ha in the zonal ecotones of forest and steppe (test sites Zhiguli and Shchelovsky Farmstead) to +(115–120) tons/ha in coniferous/broad-leaved forests near the northern boundaries of the nemoral-forest sub-zone (Green Town). The changes in carbon content in *BS* would be accordingly –25÷40 tons/ha and +85–105 tons/ha. This means that in the coming century the content of carbon conserved in skeletal phytomass of forest ecosystems of the Middle Volga River may change by ±(25–50)% and more of the base value on the average. This fact points to a quite significant regulatory role that the productivity of mixed and nemoral forests in these regions can play in their carbon exchange with the atmosphere.

(2) Global warming would induce in some cases an abrupt drop and in other cases an equally significant increase in forest productivity, and that would be directly reflected in the carbon balance and would turn out to be the key component of the mechanism of biotic regulation of the carbon cycle. The productivity of marginal forest communities in the zonal ecotone of forest and steppe would decrease most of all. In the skeletal tree-shrub pool of flat-interfluve broadleaf forests of the Zhiguli mountain range, the loss of carbon content in 2050 would be from 2–6 to 26 tons/ha and from 9–14 to 34 tons/ha according to the E GISS and HadCM3 models respectively, and by the end of the 21st century, this deficiency would reach 32 and 39 tons/ha. As a whole, the detritus branch here would contribute to further accumulation of CO_2 in the atmosphere and, jointly with the production branch, will induce *the progressing disturbance of the Le Chatelier's principle at the southern boundary of the forest belt, resulting in an intensification of global warming.*

(3) On the contrary, a significant increase in productivity was anticipated in high-plain coniferous and mixed forests of the nemoral-forest sub-zone and south strip sub-taiga zone. Mixed and dark coniferous forest biogeocoenoses would increase (and quite significantly) both their primary productivity and reserves of living organic matter. Accordingly, the conservation of atmospheric carbon in perennial skeletal phytomass of these topo-ecosystems would increase and, as a consequence, the significance of this phytocoenotic pool as a carbon sink would increase as well, (Table 3). *Positive biotic regulation of the carbon cycle would be prevalent here.* In 2050–2075, the value of additional carbon deposit in wood would be observed here from 9–11 to 38–57 tons/ha according to GISS and from 36–53 to 77–83 tons/ha according to the HadCM3; by the end of the 21st century, its values would be 38–87 and 75–105 tons/ha, respectively. Simultaneously, there would be a noticeable activation of decomposition of forest litter and humus.

The empirical data of large-scale landscape ecological surveys made it possible to calculate the carbon balance (ΔC(*Fa*) of forest formations of the Volga River basin for different scenarios of global climate changes and thereby to assess the magnitude of positive or negative biotic regulation of the carbon cycle of these zonal/regional phytocoenological units on a territorial scale (Table 4, Figures 3 and 4). A comparative quantitative assessment was conducted for comparative quantitative assessment of ecological resources of forest formations of the Volga River basin based on the specific and total values of their carbon balances under the predicted scenarios of climate change. The ecological resources of two forest categories were assessed: primary and derivative. The main predictive climate scenarios were taken from E GISS model, which gave the limits of climate changes corresponding to the purposes of the Paris Agreement. According to this scenario, the maximum reduction of anthropogenic greenhouse gases in the atmosphere and consequently the maximally weakened regional warming, were expected for two groups of primary forest formations – middle-taiga fir-spruce forests and middle and south taiga pine forests (see Table 4 and Figure 3): in each of them, the total carbon balance $[\sum \Delta C(Fa)]$ approaches +190 million tons. The subtaiga spruce and pine-broadleaf forests in the western sector of the basin had almost equally high ecological resource levels, with $[\sum \Delta C(Fa)] \approx$ +140÷170 million tons). The East-European broad-leaved forests presented 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 $\sigma[\sum \Delta C(Fa)] >$ –100 million tons. The negative balance of the marginal typical forest-steppe pine and broadleaf-pine forests increased more than twofold. On the whole, the process of climate-induced transformation of forest formations in the Volga River basin, even according to the moderate thermo-arid trend of the E GISS model, leads to a general decrease in the effectiveness of positive biotic regulation of the carbon cycle. This applied to both restored primary forests and the existing 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 for mitigating climate fluctuations.

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 quite real if the current warming trend continues. Compared to the E GISS scenario for 2200,

Table 2 Predicted partial and balance changes in the carbon content (tons/ha) relative to the base period in flat-interfluve forest biogeocoenoses in different zonal-regional conditions of the Middle and Upper Volga Region (HadCM3 model)

Parameters	Basic values	Changes in predicted periods				
		2025	2050	2075	2100	2150
a) Zonal ecotone of forest and steppe (Zhiguli low-mountain range – National Nature Park “Samarskaya Luka”)						
BS	101.75	-23.05	-27.32	-31.55	-35.78	-39.66
BV	4.16	-1.60	-1.77	-1.93	-2.10	-2.26
BR	30.25	-11.90	-14.08	-16.13	-18.06	-19.72
WD	10.24	-6.98	-7.53	-8.02	-8.45	-8.80
ML	5.35	3.56	4.90	6.34	7.78	8.99
HU	113.30	-10.54	-15.29	-18.62	-20.68	-21.66
Balance	265.05	-50.51	-61.09	-69.91	-77.29	-83.11
b) Right-bank of Sura river, mixed and broadleaf forest – National Nature Park “Chavash Forest” (test ground By-Sura)						
BS	123.42	-18.99	-14.77	-10.84	-3.31	2.90
BV	5.17	-0.60	-0.61	-0.84	-0.93	-1.13
BR	40.40	-8.88	-8.04	-7.82	-6.46	-5.64
WD	4.90	-1.06	-1.23	-1.46	-1.71	-1.91
ML	5.88	-1.28	-1.60	-2.03	-2.45	-2.79
HU	31.64	-9.76	-11.09	-11.45	-13.53	-14.76
Balance	211.41	-40.56	-37.34	-34.42	-28.39	-23.33
c) High-plain by-Volga Region, north boundary of nemoral-forest zone (Mixed forests, south of Nizhny Novgorod, “Green Town”)						
BS	134.14	13.73	26.61	38.16	49.82	60.19
BV	6.59	1.90	2.32	2.65	3.01	3.30
BR	39.48	4.44	7.99	11.09	14.28	17.06
WD	4.06	-3.46	-3.63	-3.73	-3.80	-3.84
ML	5.48	-0.13	-1.00	-1.60	-2.05	-2.38
HU	11.16	-1.71	-2.28	-2.65	-3.11	-3.43
Balance	201.36	14.77	30.00	43.91	58.15	70.90
d) South strip of mixed-forest zone, Left-bank of middle Oka river (Moraine-erosion plain, Pine-lime-oak forests, By-Oka-terrace biosphere reserve)						
BS	310.18	-27.14	-27.85	-27.76	-27.99	-27.91
BV	11.54	-1.98	-1.88	-1.89	-1.87	-1.88
BR	84.81	-4.11	-4.30	-4.28	-4.34	-4.32
WD	31.96	-7.44	-7.19	-7.21	-7.15	-7.17
ML	14.96	6.58	9.44	9.58	12.69	11.14
HU	22.05	2.84	2.52	2.55	2.48	2.51
Balance	475.50	-31.24	-29.25	-29.00	-26.17	-27.61
e) South strip of sub-taiga zone on the over-Volga Region (moraine-outwash forested lowland, Fir-pine forests, biosphere reserve “Kerzhenets”)						
BS	84.70	-13.00	-12.64	-11.86	-11.85	-1.15
BV	4.41	1.21	1.19	0.82	0.86	0.60
BR	17.08	-9.44	-9.81	-11.68	-11.60	-12.59
WD	7.85	0.40	-0.26	-0.31	-0.40	-0.64
ML	10.15	-3.91	-4.16	-4.71	-4.73	-3.45
HU	13.69	-2.45	-3.41	-3.50	-3.66	-4.09
Balance	137.88	-27.19	-29.09	-33.24	-31.38	-31.32

Notes: BS: living skeletal phytomass; BV: verdure mass; BR: root mass; WD: dead skeletal phytomass; ML: forest litter mass; HU: humus mass.

this model gives an almost threefold increase in not only summer but also winter temperatures by the end of this century. 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 adsorption.

As a result, the forest cover of the Volga River basin would acquire a predominantly positive carbon balance under extreme warming (see Table 4 and Figure 4). For example, the East-European sub-taiga broadleaf-spruce forests with weakly marked negative regulation of the

Table 3 The changes in the total carbon content (tons/ha) in different forest biogeocoenoses and in their organic components in three natural areas of preferential protection in the Oka-Volga river basin for two prognostic periods: 2050 (cooling) and 2200 (warming), according to the E GISS climate model

Characteristics		National Nature Park “Samarskaya Luka” (south forest-steppe)		National Nature Park “Chavash Forest” (typical forest-steppe)		By-Oka-Terrace biosphere reserve (south sub-taiga)	
		2050 Y	2200 Y	2050 Y	2200 Y	2050 Y	2200 Y
Groups of bio-geoco-enoses (types of sites)	1 (TE)	9.55 [–]	–12.23 [–]	77.33 [–]	90.29 [+]	20.39 [–]	29.46 [+]
	2 (TE. E)	–16.20 [–]	–38.72 [–]	46.83 [+]	63.60 [+]	–13.13 [+]	–0.44 [–]
	3 (E. T)	3.34 [–]	–27.76 [–]	–61.03 [+]	–32.51 [–]	–44.80 [+]	–27.82 [–]
	4 (E–TA)	–15.20 [+]	–58.88 [+]	12.34 [–]	31.82 [+]	13.85 [–]	29.01 [+]
	5 (TA. A)	–36.04 [+]	–65.03 [–]	7.05 [–]	27.24 [+]	7.26 [–]	11.35 [+]
	6 (Saq. EA)	1.22 [–]	–35.79 [–]	35.72 [–]	63.65 [+]	–26.02 [+]	11.82 [+]
	Average	–8.89 [+]	–39.74 [–]	19.71 [–]	40.68 [+]	–7.07 [+]	8.90 [+]

Notes: Y: year; E: eluvial; TE: transeluvial; T: transit; TA: trans-accumulative; A: accumulative; Saq: superaqual; EA: eluvial-accumulative. Flat-interfluve biogeocoenoses are in bold. The [+] sign indicates the positive regulation of the carbon cycle under the given climatic trend, and the [–] sign indicates the negative regularity.

Table 4 Total base carbon stocks, as well as total and specific carbon balances in restored primary (zonal-climax) forests Volga River basin (see Figure 1), according to the climate models of E GISS and HadCM3

Formation groups (see Table 1)	Total area spare, sq. km	The total base car-carbon reserves, 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, extreme 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)

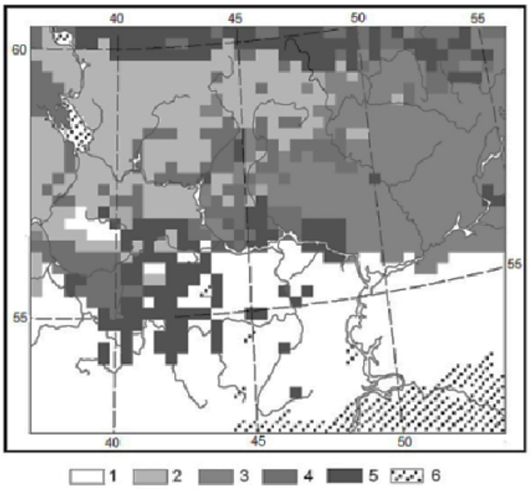

Figure 3 The distribution of the specific carbon balance in the restored primary forest formations of the Volga River basin for scenario of regional warming (2200), according to the E GISS model. Raster maps were calculated and compiled by L.S. Sharaya. Carbon balance (t / ha): 1 – (–15.0) ÷ (–7.5); 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.

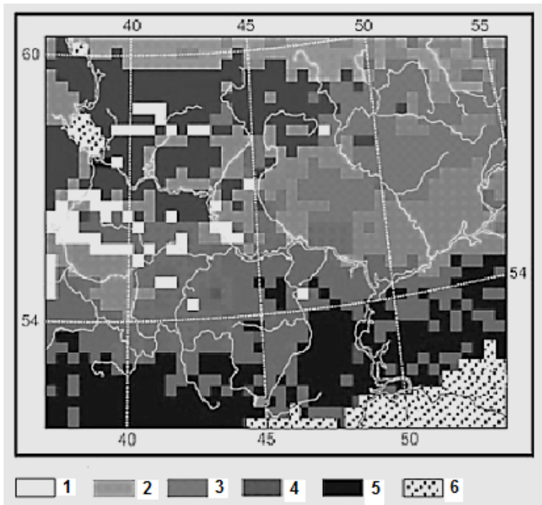

Figure 4 The distribution of the specific carbon balance (t / ha) of the restored primary forest formations of the Volga River basin for the extreme warming scenario, according to the HadCM3 model for a period of 2100. The raster map was calculated and compiled by L. S. Sharaya. Carbon balance (t / ha): 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.

carbon cycle (ΔC(*Fa*) = –7.12 tons/ha) according to the E-GISS warming scenario, would become the exhibit of substantial positive regulation (ΔC(*Fa*) = +20.01 tons/ha) under a stronger thermo-arid signal according to the HadCM3 model. Together with boreal (sub-taiga and taiga) forests, they would be capable of general positive regulation of the carbon cycle. Generally, we conclude that the *total mitigating effect of forest cover of the basin on climate changes as the hydrothermal signal becomes more intensive.*

For comparison, we present the results of forecast calculations for conifer mixed and other forests in the USA. Calculations were based on the UKMO-1987 climate model (the predecessor of the HadCM3 model). It was found that the doubling the CO_2 content in the atmosphere led to changes in carbon content from –(1.5–1.8) to +(7.8– 12.5)% [33]. Using the CBM-CFS carbon budget model developed by the Canadian Forest Service, we also found that with an average level of disturbance, the carbon stock in the phytomass of the southern taiga forests of the Volga region decreased by 7%, and the complete absence of disturbance leads to an increased in these stocks by 52% [34].

Let us turn directly to the results of our regional empirical study on solving regional experience in solving the dual problem of adsorption and adaptation. Climatic parameters were taken from the HadCM3 predictive scenarios for 2050. Plant formations with the respective indices of labile elastic resilience and changes in the carbon content were distributed by meso-catenas. In this way, an array of cartographic data was formed (more than 52,000 points). The spatial variability of the carbon balance of forests associated with their restoration potential in the basin was investigated by multiple regression methods. For this purpose, we also used the matrices of climatic parameters, 18 relief features [35], and some satellite data on the characteristics of forests (vegetation index NDVI, crown closure).

The resultant functional relationships between the carbon balance and the adaptation for zonal/sub-zonal types/sub-types of forest formations are given in Table 5. Here, $\Delta C(F_a)$ is the change in the specific flow of CO_2(tons/ha×year) in the terrestrial surface–atmosphere system; Istab(i) is the index of labile stability of a forest community; $t_{Jul}$and r_{ann} are the normalized values (in fractions of 1) of the mean July temperature and the annual precipitation; R_s is the Spearman's rank correlation coefficient. The generally low values of this coefficient stem from a large number of statistical samples (see above) with a substantial "noise" effect of local geomorphological and edaphic factors that generate groups of mean values with opposing trends. Nevertheless, the general trend of the relationships is considered statistically robust for each equation, as indicated by a significant Pearson correlation coefficient P. Each zonal–subzonal type and subtype includes primary and derived forest communities, as well as fragmented timberlands; *i.e.*, these units represent the state of the existing forest cover.

Table 5 Equations of the connections of carbon content change in forest formations of the Oka River basin with their elastic-plastic functional stability and the climate characteristics

Plant formations	Regression equations	R_s	P
A. Spruce and broadleaf-spruce forests; middle- and south-taiga and sub-taiga	$\Delta C(\text{Fa}) = 62.4 \cdot I_{\text{tab(i)}} + 22.7 \cdot r_{\text{ann}} + 10.2 \cdot t_{\text{Jul}} - 49.3$	0.50	$< 10^{-6}$
B. Pine south-taiga forests	$\Delta C(\text{Fa}) = 38.6 \cdot r_{\text{year}} + 29.4 \cdot t_{\text{Jul}} - 16.0 \cdot I_{\text{tab(i)}} - 24.8$	0.46	$< 10^{-6}$
C. Broadleaf-pine forests, sub-taiga	$\Delta C(\text{Fa}) = 217.4 \cdot I_{\text{tab(i)}} + 78.0 \cdot t_{\text{Jul}} + 55.3 \cdot r_{\text{ann}} - 165.6$	0.64	$< 10^{-6}$
D1. Northern broadleaf forests, with an admixture of spruce	$\Delta C(\text{Fa}) = 6.23 \cdot I_{\text{tab(i)}} - 4.65 \cdot t_{\text{Jul}} + 4.30 \cdot r_{\text{annr}} - 5.63$	0.46	$< 10^{-6}$
D2. Southern steppified broadleaf forests	$\Delta C(\text{Fa}) = 32.9 \cdot t_{\text{Jul}} + 24.1 \cdot r_{\text{year}} - 54.3 \cdot I_{\text{tab(i)}} - 19.6$	0.38	$< 10^{-6}$
E. All formations of the Oka River basin	$\Delta C(\text{Fa}) = 76.3 \cdot I_{\text{tab(i)}} + 36.9 \cdot t_{\text{Jul}} + 31.1 \cdot r_{\text{ann}} - 69.6$	0.13	$< 10^{-6}$
G. All formations of primary forests	$\Delta C(\text{Fa}) = 68.6 \cdot t_{\text{July}} + 37.1 \cdot r_{\text{ann}} - 3.4 \cdot I_{\text{tab(i)}} - 51.0$	0.16	$< 10^{-6}$
H. All formations of secondary forests	$\Delta C(\text{Fa}) = 123.5 \cdot I_{\text{tab(i)}} + 22.8 \cdot r_{\text{ann}} + 18.7 \cdot t_{\text{Jul}} - 64.6$	0.30	$< 10^{-6}$
I. Secondary forests in place of pine	$\Delta C(\text{Fa}) = 2218 \cdot I_{\text{tab(i)}} - 68.5 \cdot t_{\text{Jul}} + 33.9 \cdot r_{\text{ann}} - 83.2$	0.45	$< 10^{-6}$
K. Secondary forests in place of broadleaf	$\Delta C(\text{Fa}) = 10.7 \cdot I_{\text{tab(i)}} + 6.0 \cdot r_{\text{year}} - 4.6 \cdot t_{\text{Jul}} - 12.2$	0.13	$< 10^{-6}$
L. Forests of the southern forest-steppe and northern steppe	$\Delta C(\text{Fa}) = 95.4 \cdot t_{\text{Jul}} - 78.3 \cdot I_{\text{tab(i)}} + 47.5 \cdot r_{\text{ann}} - 22.6$	0.54	$< 10^{-6}$

Equations derived are proposed to be included directly in the "Guidelines for the quantitative determination of the adsorption volume of greenhouse gases" for boreal and nemoral forests in conditions similar to the East-European Plain.

For example, Table 6 shows the results of calculations (by formulas in Table 5) of predicted specific and total values of the carbon balance of zonal/sub-zonal types/subtypes of forest formations of the all Oka-Volga River basin concerning basal and predicted values of Istab(i), as well as by the t_{July} and r_{ann} parameters prescribed by two different global climate prediction models. According to the moderate model GISS-93, the warming in the Middle Volga Region will be from 0.2–0.6^0 in winter to 0.8–1.1^0 in summer by the middle of the XXI century, which corresponds to the Paris Agreement Compatible Scenario (2015). The extreme model HadCM3 gives the annual temperature increase of 2.5–4.0^0 for this period, which can occur at the current rates of global warming [13, 14].

The results of the calculations of $\Delta C(Fa)$ were quite similar to the data obtained by other methods [23], though there were some differences. According to the climate scenario for 2100 based on the HadCM3 prediction model, there was almost the same average specific carbon balance of forest cover in both cases (11.05 and 10.02 tons/ha×yr, respectively). The maximum adsorption capacity was due to sub-taiga forest formations; however, it was typical of dark-coniferous/broadleaf forests in the former case and shifts to the pine/broad-leaved forests, with a dramatic increase in this maximum, in the latter case.

The total elastic-plastic resilience of forest formations must be increasing during the entire 100-year period of prediction (to the greatest extent under extreme warming). Hence, one should also expect a significantly enhanced greenhouse gas adsorption capacity of boreal forests, *i.e.*, an increase in their ecological resources (see Table 5). The comparison of values of the carbon

Table 6 The specific and total values of carbon balances of forest formations in the sample area of the Volga River basin, projected for 2100 with their base and final labile elastic stability and climatic scenarios, according to two global forecast models: moderate GISS-93 and extreme HadCM3

Zonal types and sub-zonal subtypes of forest formations	Weighted average index of resilient stability, $I_{resili(1)}$			Climatic parameters projected for 2100				Specific carbon balance, t/ha		Wooded area, km^2	Total carbon balance, million tons	
	Base	Projected		GISS-93 model		HadCM3 model						
		GISS-93 model	HadCM3 model	t_{July} °C	r_{year} mm	t_{July} °C	r_{year} mm	GISS-93 model	HadCM3 model		GISS-93 model	HadCM3 model
A. Spruce and broadleaf-spruce forests, middle- and south-taiga and sub-taiga	0.554	0.630	0.670	20.1	950	22.2	725	9.70 14.44	8.87 16.04	75706	73.435 109.319	67.151 121.432
B. Pine south-taiga forests	0.430	0.630	0.675	20.1	930	22.6	710	9.23 6.03	12.82 8.90	48506	44.771 29.249	62.185 43.170
C. Broadleaf-pine forests, subtaiga	0.531	0.664	0.684	21.6	830	23.0	705	18.70 57.83	44.51 82.76	37841	70.763 218.835	160.430 313.172
D1. Northern broadleaf forests, with an admixture of spruce	0.547	0.667	0.689	22.2	780	23.8	685	-5.58 -2.32	-5.26 -3.61	18350	-10.239 -4.257	-9.652 -6.624
D2. Southern steppified broadleaf forests	0.547	0.667	0.689	23.8	700	24.0	650	-14.00 -17.86	-10.83 -18.57	7544	-10.562 -13.434	-8.170 -14.009
Waterlogged coniferous forests and forest swamps	0.549	0.630	0.672	20.1	940	22.4	720	8.12 13.17	6.61 14.18	7052	5.726 9.287	4.661 10.000
Nemoral floodplains	0.559	0.642	0.685	22.5	770	23.6	680	3.37 3.13	4.69 11.53	16267	5.482 5.092	7.676 18.871
Weighted average / Sum	0.517	0.634	0.673	20.4	921	21.0	717	3.61 11.62	10.02 17.10	211266	179.376 354.091	284.281 486.012

Notes: t_{July} is the average temperature in July; r_{year} is the annual amount of precipitation. In the columns of the specific and total carbon balance, the first row characterizes the balance at the base value of the stability index of plant formations, and the second – at its final value (for the forecast period of 2100). Treeless raised and transitional bogs are not counted.

balance of forest formations obtained for the initial (basal) and final (total) resilience indices shows an unambiguous pattern of considerably increasing adsorption capacity of boreal forests with the increase in their restoration potential.

However, these calculations did not take into account changes in the ecological resources of forest formations, which were caused by their functional and structural transformations throughout the prediction period. These changes were not uniform. According to the climate scenarios of moderate warming (GISS-93 and E GISS), algebraic addition of the ΔC(*Fa*) values was performed for the zonal/sub-zonal types/sub-types of forest formations in the Oka-Volga River basin (see Table 5). The following *indices of changes in the specific carbon balance of forests* [ΔC(*Fa*)] have been obtained (tons/ha): **A** (+4.998); **B** (–14.570); **C** (+27.773); **D1** (+10.010). Generally, the ecological resources of the full range of boreal dark-coniferous and dark-coniferous–broadleaf forests, as well as subtaiga pine–broadleaf forests, were preserved. The adsorption capacity of broad-leaved forests also noticeably increased (mainly due to their transformation into boreal forests). At the same time, pure south-taiga pine forests, being transformed by more than 50% into mixed forest communities, substantially lost their ecological resources, though their ΔC(*Fa*) remained positive.

The data presented indicate, even more clearly than has been shown previously, the phenomenon of an increase in the sequestration capacity of forest cover in the Oka-Volga River basin with the intensification of global warming intensity and a corresponding increase in the elastic-plastic resilience of ecosystems. This finding is further supported by a comparison of ΔC(*Fa*) values derived from the GISS-93 and HadCM3 models. *The increase in forest restoration potential, a key ecological factor, makes a decisive contribution to the enhanced sequestration of greenhouse gases.*

6 Conclusion

In general, the research carried out represents a meaningful step towards translating **the conceptual ideas of V. G. Gorshkov [16], A. I. Utkin [17], and K. S. Losev [6]—who synthesized these ideas—*about the ecological resources of forests into a full-fledged scientific and methodological concept. Assessing the results of this research, we fully agree with the insightful comment by A. Z. Shvidenko that "... numerical predictions of models... should be considered... rather as food for thought about the potential future trajectories of forest ecosystems..., taking into account the considerable uncertainty of the forecasts" [36, 37]. Our predictive landscape-ecological analysis of the carbon cycle regulation by forest cover in the Volga River basin is inherently probabilistic.

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Conflict of interest

The author declares no conflicts of interest in this paper.

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