

## Ecological Resources of Boreal Forests in the Adsorption of Greenhouse Gases and in Adaptation to Global Warming (To the Paris Agreement on Climate Change)

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### Abstract

One of the most important ways to achieve the goals stipulated by the Paris (2015) Agreement on Climate Change is to solve a two-fold task: 1) the absorption of CO<sub>2</sub> by the forest communities from the atmosphere during global warming and 2) their adaptation to these climate changes, which should ensure the effectiveness of adsorption itself. Given report presents the regional experience of the numerical solution of this task. Calculations of the carbon balance of forest formations in the Oka-Volga River basin were carried out for global forecasts of moderate and extreme warming. The proposed index of labile elastic-plastic stability of forest ecosystems, which characterizes their succession-restorative potential, was used as an indicator of adaptation. For the territory of the Oka river basin using multiple regression methods, a numerical experiment was conducted to assess the effect of the elastic stability of forest formations and the predicted climatic conditions on the carbon balance. A total of 11 linear equations were obtained (with a significance level of  $P < 10^{-6}$ ). In the upcoming 100-year forecast period, the overall elastic-plastic stability of forest formations should increase, and to the greatest extent with extreme warming. Accordingly, one should expect a significant increase in the ability of boreal forests to absorb greenhouse gases. A comparison of the carbon balance values of forest formations obtained with initial (base) and final (final) stability indices gives an unambiguous picture of a significant increase in the adsorption capacity of boreal forests with an increase in their regenerative potential. A decisive contribution to increasing the adsorption of greenhouse gases is made by the growth of reforestation adaptation, which plays the role of a direct environmental factor.

**Keywords:** forest ecosystems, global warming, adsorption of greenhouse gases, adaptation of the forests to the climate change, predictive empirical-statistical modeling

### 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 (Morozov, 1949; Sukachev, 1972). 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 (Isaev, 2012).

The forest cover, which passes atmospheric moisture through itself and increases its transpiration abruptly into 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 (Gorshkov et al., 1999), 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" (Puzachenko, 2010, p. 112).

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 (Kellomäki et al., 2008). It is 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 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 (Albritton et al., 2003). However, the real picture is much better than these calculations. The current warming trend will lead to an increase in average global temperature by 4° by 2100 (Le Quéré et al., 2015). At the same time, regional warming in the territory of Russia can be on the order of 6–11° (Shvidenko et al., 2017).

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 (Paris Agreement, 2015). Following the Paris Climate Change Agreement, *measures should be taken for the 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).

Thus, the Paris Agreement presupposes the necessity to assess the role of forest ecosystems in carbon cycle regulation and stabilization of the environment at the continents via the processes of greenhouse gas adsorption. One of the most important trends of this strategy is to use forests for climate change mitigation (Shvidenko et al., 2017) by the mechanisms of biotic regulation of the carbon cycle.

On the other hand, an important goal of the Paris Agreement is the planning of actions in the field of the adaptation “strengthening adaptive capacities, increasing resilience and reducing the vulnerability of socio-economic and ecological systems to climate change, to promote sustainable development and ensure an adequate adaptive response in the context of the above temperature target” (Article 7 of the Agreement).

Thus, the necessity of solving a *two-unified task for forest ecosystems – adsorption and adaptation* – has been identified, which will make it possible to assess the regulation of the carbon cycle by the forest cover, aimed at mitigating contemporary global warming.

The given report describes the experience of the regional solution of this two-unified problem on the example of the Oka-Volga River basin. A numerical experiment was carried out to assess the influence of elastic-plastic stability of forest ecosystems as an indicator of their adaptive potential, as well as predicted climatic parameters on the carbon balance of forests, i.e. on their adsorption capacity.

### Ideological Foundations of The Scientific Research

The ideological basis of our research into the above problem was the new environmentally-oriented paradigm in the doctrine of forest put forward in the works (Gorshkov, 1994; Utkin, 1995; Losev, 2001). 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 its production under varying 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 (Utkin, 1995), i.e., the leading “ecosystem services” of forest cover (Tishkov, 2005). 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* (Shvidenko et al., 2014, p. 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 (Gauthier et al., 2015).

Thus, the concept of ecological resources of forest ecosystems should be expanded to include their ability to adapt to a changing climate. The adaptive properties of forests were quantified by indicators of their functional stability based on the parameters of the biological cycle (Kolomyts et al., 2015). We will consider the dual problem of ecological resources of forest ecosystems: on the one hand, their “work” on additional adsorption/emission of CO<sub>2</sub> during global climate changes, and on the other, the degree of sustainability of their functioning under the conditions of these changes.

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 (Gorshkov, 1994; Utkin, 1995) is from 3.45 to 4.65 million km<sup>2</sup> according to various estimates, i.e., up to one third of all virgin forests in the world (Losev, 2001). At the same time, almost half of them are boreal forests providing more than 90% of the carbon sink of all boreal forests worldwide (Shvidenko et al., 2014). In bioclimatic interpretation, these are the climax or related quasiclimax (coniferous, mixed and broad-leaved) forest communities representing the final stage of endo-eco-genetic (restorative) successions, according to (Sukachev, 1975). 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 (Utkin, 1995). 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*.

### Materials and Methods

The local basic and forecast analysis was based on the materials of large-scale landscape-ecological surveys carried out by the authors and their colleagues (1987–1996) at six experimental test sites (ranges) of the Middle Volga Region (Figure 1). These test sites were chosen on the zonal ecotones where the phytocoenoses are most sensitive to climate changes. They embrace a wide range of zonal transitions from south forest-steppe to mixed forests (southern-taiga appearance) and characterize the main diversity of zonal transitions on the boreal ecotone of eastern sector of the Russian Plain. Let us to enumerate this test sites:

- (1) The zonal ecotone of forest and steppe – oak forests and steppified pine forests of the Zhiguli low-mountain range (the region of “Samarskaya Luka” National Nature Park);
- (2) The sub-taiga/forest-steppe ecotone – pine, mixed and broadleaf forests of the high right-bank Prisyrye (the region near the Sura

river, the territory of “Chavash Varmane” National Nature Park); (3 and 4) The boreal-nemoral forest ecotone – coniferous, mixed and broad-leaved forests of high-plain by-Volga region (the right-bank region of the Volga River) in the vicinity of Nizhny Novgorod; this compound ecotone system consists of two subsystems: (2) erosion loamy plain with maple-lime oak and aspen forest (stow “Shchelokovsky Farmstead”) and (4) moraine-outwash plain with spruce, pine and spruce-lime oak forests (stow “Green Town”); (5) Outwash forested lowland of the Oka-Tesha region (the right-bank strip of the Oka River) – pine forests and subors near the boundary between the mixed forest zone and the nemoral-forest subzone (surroundings of the town of Vyksa, Nizhny Novgorod region); (6) Moraine-outwash lowland on the trans-Volga region (north of Nizhny Novgorod) – spruce and pine forests in the southern strip of the zone of mixed forests (“Kerzhensky” Nature Reserve); (7) Sub-zone of northern forest-steppe in high-plain by-Volga region; lake-alluvial sandy and loamy plain on right-bank of Volga, near of its small lateral inflow – Kud’ma river; oak-lime and pine, with spruce, forests; (8) South boundary of sub-taiga zone; lowland moraine-outwash plain on the Middle left-bank region of by-Oka river; mixed-, conifer-, broad- and small-leaves forests (By-Oka-Terrace biosphere reserve).

Each of these test sites characterizes a particular regional ecosystem, with the corresponding conventional name: 1 – Zhiguli, 2 – By-Sura (Prisurye), 3 – Shchelokovsky Farmstead (Hutor), 4 – Green Town (Zeleny Gorod), 5 – Vyksa, 6 – Kerzhnets, 7 – Kud’ma, 8 – By-Oka-Terrace Reserve (BOTR).

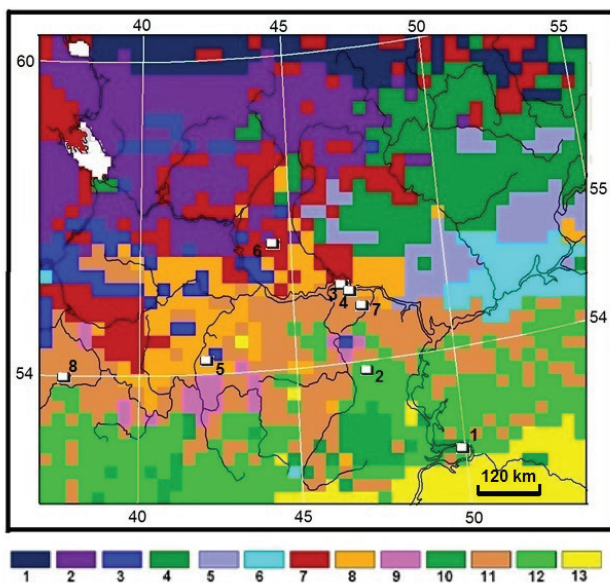


Figure 1. Raster base map of zonal-provincial groups of indigenous plant associations (modern + restored) on the territory of the main drainage basin of the Volga River basin. The map is designed and compiled with the participation of L.S. Sharaya. Symbols are in Table 1.

On each test site, the empirical information (statistical sample of geocomponent signs) included about 80 characteristics of the structure-functional state of forest to-pocosystems. These characteristics consisted of 5 blocks: (1) hydro-geomorphological; (2) soil morphological; (3–4) phytocoenotic structural and functional; and (5) landscape-geophysical. Collection of factual material at each point, its processing, and subsequent calculations were made in accordance with the known methodical regulations. The transition from local to regional levels (at the scales from 1:2,000,000 to 1:4,000,000) was carried out using the developed

method of *inductive-hierarchical ex-trapolation*. 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.

Each type or sub-type of the plant formation shown in a small scale geobotanical map is identified by a specific group of biogeocoenoses from the upland-extrazonal series characterizing the regional spatially ordered (micro-catenary) system of local zonal structure that is adequate to the vector of the predicted climate changes and, hence, may serve as a model of the main trends of ecosystem rearrangements. Then, each range of this formation is presented as a *polyvector set of mesocatenae* and is subdivided into regional types of localities or meso-geotopes, from the eluvial and transeluvial types to the accumulative and super-aquatic ones, according to the landscape-geochemical classification (Polynov, 1956; Glazovskaya, 1964). For this purpose, new methods of geomorphometric statistics are used, with the results corrected on the basis of the landscape and soil maps. An intermediate map of the types of meso-localities is drawn for the entire forested part of the region. Assuming mesocatenae to be a homomorphic image of micro-catena, we assign biogeocoenoses of each previously identified group to mesogeotypes of the corresponding geobotanical range. The resultant vegetation-catena mosaic is then filled with the basic or prognostic metabolic parameters of biogeocoenoses, which are now used as local representatives of different zonal/regional types or subtypes of the geographic environment.

According to Sukachev (1975), 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. According to the rules of classical phytocoenology (Sochava, 1979), the phytocoenological unity identified here refers to the classes (and sub-classes) of plant formations that are regional variants (for example, Eastern European or Kama-Pechersk) of the types and subtypes of vegetation (middle taiga, sub-taiga, etc.). The Volga River basin accounts for 13 groups of indigenous plant associations.

Figure 1 shows a basic raster map of zonal-provincial groups of plant associations of the Volga River basin. The map is based on the Vegetation Maps of the European Part of the USSR (Gribova et al., 1980; Kotova, 1987). These maps reflect the spatial structure of the forest cover of European Russia approximately at the time when we conducted large-scale landscape surveys. This was the time of the end of the base period 1885–1986, after which, as is known (Houghton et al., 1996), modern global warming began. Thus, we can speak about the full temporal correspondence of the analytical material obtained by us on the state of the forest formations of the Volga river basin with their distribution areas presented on the indicated geobotanical maps.

The ranges of each phytocoenological group included indigenous forest communities (dark and light coniferous, mixed) – both modern and restored on the site of long-derivative (small-leaved – birch and aspen) forests, as well as agro-landscape complexes. Thus, this map is a *model of the potential bioclimatic forest system of the Volga River basin*. It reflects the zonal-provincial phytoclimatic 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 will be given, which is very important for comparison with the predicted carbon balance of real forests. It will also be shown how the regulatory role of the boreal and

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

Plant formations, by (Gribova et al., 1980)			Groups of plant associations	
Zonal types and classes	Regional ver-sions	Sub-zonal sub-types	Brief characteristics	Number and symbol
Dark conifer and broadleaf–dark conifer forests (secondary aspen –birch)	East European (Upper Volga region)	Middle taiga	Spruce green mosses with Small shrubs	1
		South taiga	Spruce small shrub-grass	2
		Sub-taiga	Broadleaf-spruce complex nemorose-herbal	3
	Kama – Pechora – West Ural region	Middle and south taiga	Fir-spruce and spruce-fir grass-small shrub, with green mosses, and grass	4
		Sub-taiga	Fir-spruce complex nemorose-herbal	5
			Broadleaf–fir–spruce nemorose–herbal	6
Pine and broad-leaf–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 under-growth) small shrub-grass	8
			Broadleaf-pine and pine complex, with spruce	9
		Forest-steppe and steppe	Pine and broadleaf-pine, with steppe undergrowth, and herbs-cereals	10
Broadleaf forest	East European	Northern forest-steppe	Lime-oak and oak	11a
			Lime with admixture of other broadleaf kinds	11b

memoral 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 centuries-old anthropogenic transformation and generally deforestation.

Next phytomass parameters (tons/ha) have been used for calculation of carbon balance: (1) skeletal wood mass, *BW*; (2) skeletal tree-shrub phytomass, *BS*; (3) total living above-ground phytomass, *BL*; (4) total verdure mass, *BV*; (5) root mass, *BR*; (6) forest litter mass, *ML*; (7) debris – dead skeletal mass (brushwood and dead-wood), *WD*; (8) humus mass in organic-mineral layers of the soil, *HU*; (9) annual growth from trunk wood, *PW*.

Live phytomass were calculated by the general and regional tables of biological productivity of fully stocked (normal) stands (Shvidenko et al., 2008) 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 their carbon content was performed using the known carbon coefficients (Kobak, 1988; Utkin et al., 2006).

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 at the specified variants of climate prediction for a particular period. The potential of biotic regulation of the carbon cycle was assessed by the hydrothermal ordination of discrete metabolic parameters of forest ecosystems under different zonal-regional and local conditions of the Oka-Volga River basin.

The thermo- and hydro-edaphic ordination of metabolic characteristics of topo-ecosystems was made by two geophysical parameters (Figure 2): the temperature of soil 50 cm deep ( $t_{50}$ ) and summer productive moisture reserves in the 0–50 soil layer ( $W-50$ ). This parameter is most closely connected with atmospheric humidification. The functional characteristics of forest ecosystems also show the highest correlation with these pa-rameters. However, this signal must be constantly acting and unidirectional, and this is its effectiveness. Correlation connections are not always rather high though quite significant (Pirson’s test of significance,  $P \ll 0.05$ ). The  $R^2$  values ranged from 65–75% to 25–35%. At the weak

connection, 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.

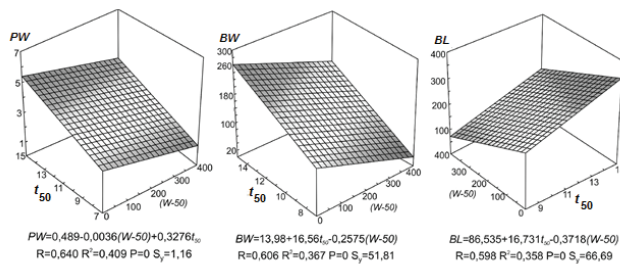


Figure 2. Linear distribution surface of biological cycle parameters in space of soil hydrothermal factors on the mixed forests of the boreal-nemoral forest ecotone, regional ecosystem “Green Town”, experimental test site 4 (see in the Figure 1).

Statistical characteristics: R and  $R^2$  – coefficients of correlation and determination; P – Pearson’s test of significance.

As is known [Montgomery and Peck \(1982\)](#), violations of the basic principles of statistical analysis are inevitable when describing complex multicomponent biological systems. In particular, the principle of linear independence of predictors is not observed, and the correlation and determination coefficients cannot be high. Dissymmetrization and fragmentation of hydrothermal niches, with a predominantly Poissonian distribution of biogeocoenotic units, indicate a complex process of their climate-genic transformations differentiated in space ([Kolomyts, 2008](#)). The main task of 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.

For estimating changes in the carbon content of individual biotic components and forest biogeocoenoses in general, we used the traditional forest-management method ([Morozov, 1949](#); [Kobak, 1988](#)) based on the estimation of the dynamics of live phytomass and necromass (and the humus mass), which yields the best results in  $CO_2$  balance calculations over long periods. This method gives the best results at balance assessments of the carbon cycle components for long of time. The change  $\Delta C(Fa)$  of the mass of carbon flow in the system of soil-plant-atmosphere can be presented as follows:

$$\Delta C(Fa) = \Delta C(Rm) - \Delta C(NPP), \tag{1}$$

where Fa is  $CO_2$  flow above the plant cover; Rm is  $CO_2$  emission as a result of vital activity of soil and above-ground saprotrophs (mainly bacteria and fungi) which decompose humus, forest litter, and skeletal dead mass; NPP is pure primary production of biogeocoenoses (above-ground + root). Using the considered discrete parameters of the minor biological cycle (see above), the equation (1) can be written in expanded form:

$$\Delta C(Fa) = \Delta C(WD) + \Delta C(ML) + \Delta C(HU) - \Delta C(BS) - \Delta C(BV) - \Delta C(BR). \tag{2}$$

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

Each member of the right part of the equation (2) may have both positive and negative values. At positive values, the first three items give an increase of  $CO_2$  emission from soil-plant cover into the 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 released into the atmosphere decreases, while the autotrophic biogenesis becomes less intensive into atmosphere decreases, while the autotrophic biogenesis becomes less intensive and consumes less  $CO_2$ , 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  $DC(Fa)$  is formed, which must 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, becomes a source of its additional emissions. In the former case, there is negative feedback directed at the realization of Les Chatelier’s principle for 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 greenhouse effect of the atmosphere and, consequently, the warming itself. It should be emphasized that the values of the parameter  $\Delta C(Fa)$  calculated by Eq. (2) characterize the dynamic carbon balance of forest ecosystems due to changes in the balance of the deposit and carbon 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 – as the ratio of forecast balances to the balance at the end of the base period. The dynamic balance is fundamentally different from the traditional static carbon balance, which is calculated for given conditions in a stationary climate (or without taking into account any climatic changes).

Labile (phytocoenological) plastic-elastic functional stability of forest ecosystems was considered as an indicator of their adaptation. This parameter is characterized by two complex discrete parameters of metabolism ([Bazilevich and Rodin, 1969](#); [Krut’ko et al., 1982](#)): the coefficient of the annual turnover of the above-ground phytomass ( $CR = PV/BL$ ) and the forest litter-fall index ( $CY = PV/LM$ ). In the abovementioned equations, PV is the annual production of green mass, BL is the total living above-ground phytomass, and ML is the mass of the forest litter. Both parameters characterize the initial transportation of organic matter and energy in the entire trophic chain and thus characterize the impact of plant mass in the stable functioning of the ecosystem.

Considering further the system stability as a relative deficiency of its changeability and using the measure of Euclidean distance, we obtain the following expression for the calculation of the normalized index of functional stability  $Istab(i)$  of  $i$ -th ecosystem:

$$Istab(i) = 1 - \frac{\sqrt{(\Delta CR_i)^2 + (\Delta CY_i)^2}}{\sqrt{2}}, \tag{3}$$

Where  $(\Delta CR_i) = (CR_{max} - CR_i) / (CR_{max} - CR_{min})$ ;  
 $(\Delta CY_i) = (CY_i - CY_{min}) / (CY_{max} - CY_{min})$ .

Index  $i$  is the number of the investigation plot. The maximums and minimums of CR and CY are taken over  $i$ . Therefore, the stability index is evaluated in dimensionless units. If CR<sub>i</sub> approaches CR<sub>max</sub> and CY<sub>i</sub> approaches 0, then  $Istab(i)$  approaches 1. It can be seen that both prognostic parameters are considered equivalent and are

accepted with weights equal to 1. The minimum and maximum *CR* and *CY* are taken from a particular statistical sample; hence, it is obvious that each of the indices characterizes the relative but not absolute stability of the ecosystem within the sampling area. The index shows, which part of the maximum possible stability is typical of a particular natural complex. Parameter *Istab(i)* of a forest ecosystem characterizes its ability to undergo restorative successions (elasticity), or to transition to a new functional stable state, while maintaining, with an acceptable probability, its primary structure (plasticity).

In practice, the parameter *Istab(i)* can be calculated using the following empirical formulas, with sufficiently high determination coefficients  $R_2$  (Kolomyts, 2008):

$$Istab(i) = 0.715 - 0.0555 \cdot CY; \quad R_2 = 0.90; \quad (4)$$

$$CY = 0.0.993 \cdot t_{Janv} - 0.5365 \cdot t_{July} + 0.003508 \cdot r_{ann}; \quad R_2 = 0.61; \quad (5)$$

$$CY = \exp(6.453 - 0.2993 \cdot t_{July}); \quad R_2 = 0.76 \quad (6)$$

Here  $t_{Janv}$  and  $t_{July}$  are the average temperatures of January and July (in °C), respectively,  $r_{ann}$  is the annual amount of precipitation (in mm).

The distribution pattern of the labile and resist stability indices of forest formations is shown in Figure 3. The lower stability of the both types is typical for the indigenous medium and southern taiga spruce and broadleaf-spruce subtaiga forests allocated to the extremely northern part of the Volga River basin ( $Istab(i) = 0.35-0.37$ ). Their derived small-leaved forests are characterized by somewhat higher regeneration potential ( $Istab(i) = 0.41-0.45$ ). Higher sensitivity to climate variations but less developed mechanisms of functional regeneration ( $Istab(i) = 0.36-0.40$ ) are revealed for pine forests of medium and southern taiga allocated to the interfluves on the left banks of the Volga, Unzha, and Vetluga rivers. The contrast is more pronounced in the broadleaf-pine forests of the sub-taiga zone in the lowlands of the Trans-Volga Region and the lower reaches of the Oka River. They are very sensitive to the external effects but are capable of relatively quick functional regeneration ( $Istab(i) \geq 0.46-0.50$ ). A similar ratio between the re-sistance and resilience is typical for small massifs of broadleaf forests in the basins of the Moksha and Sura rivers and the middle reaches of the Oka river.

As a whole, there are three bands of prevailing values of taxonomic norms of elastic-plastic stability of forest ecosystems (see Figure 3). The bands are directed sub-latitudeally – from WSW to ENE. The first of them stretches almost along the entire left bank of the Oka, interrupting in its very lower reaches. It covers the slopes of the Smo-lensk-Moscow ridge, as well as the northern outpost of the Central Russian Upland. This band of maximum values of  $Istab(i) - 0.55-0.65$ . The second, the same continuous, strip is formed by the northern part of the Central Russian Upland (regions of Orel and Tula), then the Meshcherskaya lowland and the following Nizhneoksko-Teshinsky lowland plain. Here, on the contrary, the parameter  $Istab(i)$  becomes the smallest –  $0.44-0.53$ . The third sub-latitudeal strip in the basin is represented fragmentarily – by the upper reaches of the river. Oka, Ryazan Meshchera, and the basin of the lower reaches of the river. Moksha. Here again, increased elastic-plastic stability is observed (up to  $0.53-0.61$ ). Thus, there is no clear link between the stability index of forest formations in the Oka-Volga River basin and the main elements of the plain relief. Low values of  $Istab(i)$  are characteristic of both the northern part of the Central Russian Upland and the Oka-Don Lowland.

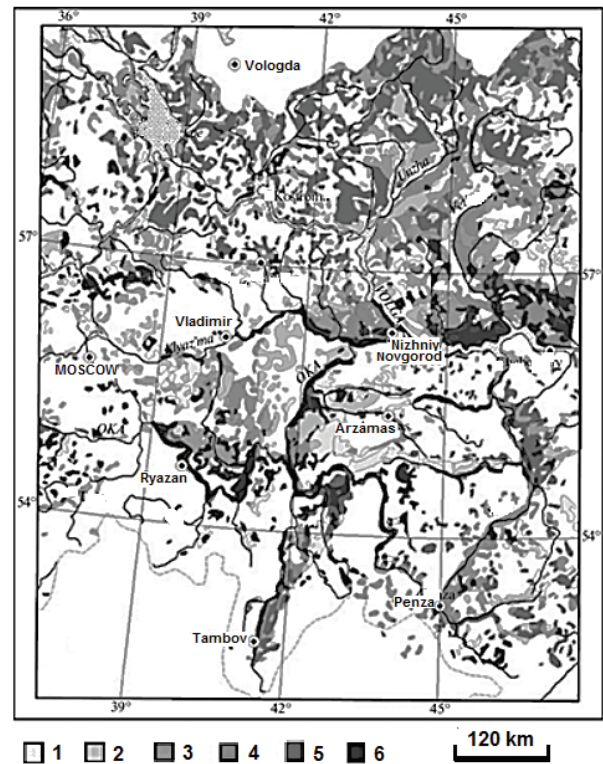


Figure 3. Average values of the indices of elastic-plastic stability of forest associations of the Volga River basin. Indices of the  $Istab(i)$  parameter: 1 – 0.260–0.335; 2 – 0.335–0.365; 3 – 0.365–0.393; 4 – 0.393–0.435; 5 – 0.435–0.465; 6 – 0.465–0.580.

The quantitative approaches to prognostic ecological-geobotanical mapping recently developed abroad (MacMillan et al., 2009) are intended for drawing large-scale maps. However, these approaches have never been used for drawing prediction maps on a time scale. Moreover, we do not know of any experience in using these methods for map-ping the functional parameters of forest ecosystems in the framework of a global climatic scenario. In landscape ecological analysis, we use approaches based on *new geomorphometric methods* (Shary et al., 2002; Sharaya, 2007) for drawing spatiotemporal maps.

The procedure of regional mapping was performed using the vegetation maps for the Eu-ropean part of the former USSR at the above-mentioned scales compiled in the 70s–80s of the last century (Kotova, 1987; Montgomery and Peck, 1982), i.e., approximately at the time when we made large-scale landscape surveys. It was the time of termination of the basal period of 1985–1986, after which, as is known (Houghton et al., 1996), modern global warming began. Thus, here we can speak about the complete temporal conformity of the analytic data on the state of forest formations of the Oka-Volga River basin that we obtained with the areas of their distribution shown on the above geobotanic maps. The contents of these maps were used as the initial factual material for basal and predictive calculations, including those of the carbon balance of forest formations. According to (Sochava, 1979), phytocoenological units on these maps (see Figure 1) belong to the classes (and sub-classes) of plant formations, which are regional variants (e.g., East Europe-an, or Kama-Pechora) of the types and sub-types of plants – middle taiga, southern taiga, sub-taiga, etc. (see Table 1).

It would be interesting to find out how outdated are the Geobotanic Maps of European Russia of the 70–80s of the past century that

we have used? Based on the data of official stock-taking of the USSR Forest Fund, which was made every 5 years beginning from 1968, it was shown (Isaev, 2012) that the area of forested and non-forested lands in the European part of Russia changed by only 6–8% throughout 1968–2008. There were also minor shifts in the species structure of forests. The proportion of coniferous species on the forested lands decreased by 4%; the proportion of soft-leaved species increased by 5%; the “species structure of hard-leaved forests remained relatively stable” (ibid. 39). The ratio of areas with the different age structures of forests changed insignificantly.

The newest Map of Forest Ecosystems of Northern Eurasia, compiled using satellite data from SPOT-Vegetation (Bartalev et al., 2003), 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, 1972). Such forest categories do not at all correspond to the meaningful meaning of the concepts of “classes of plant formations” and “types of vegetation” (Sochava, 1979) accepted in traditional geobotany (Kotova, 1987).

The maps of the basic and predicted metabolic parameters based on statistically significant relationships between the functional characteristics of the ecosystems and the terrain (Figure 2) allow the changes in the metabolic parameters to be quantitatively estimated with allowance 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 contents of different pools of forest biogeocoenoses in a given ecoregion, we used NASA satellite data on the terrain, namely, the matrices of elevations of the earth 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 the year 2000 (ftp://e0dps01u.ecs.nasa.gov/srtm/).

The regional scenario of anthropogenic climatic changes in the ongoing century was taken from the two global prognostic models of the atmosphere–ocean coupled general circulation models (AOGCMs): 1) moderate global prognostic climatic E GISS model (Hansen et al., 2007), with her earlier version GISS-93, and 2) extreme HadCM3 model, Version A2 (Pope et al., 2000). The E GISS 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  $-0.5 \div 1.90$  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  $0.5 \div 0.70$  with a decrease in  $F_{hum}$  to 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, without a definite binding of the forecast scenario to a particular date.

However, the currently existing warming trend can (see above) is adequate to the climate prediction by the extreme model HadCM3, 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 (Kellomäki et al., 2008). The results of our landscape-ecological studies based on this model describe a quite probable pattern of dramatic aridization of the natural environment in this part of the East-European subcontinent over the next 100–200 years.








**Results and its Discussion**




**Carbon balance of forest associations of the Volga River basin.**

The empirical data of large-scale landscape ecological surveys made it possible to calculate the carbon balance ( $\Delta C(Fa)$ ) 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 2, Figures 4 and 5). It was given an account of comparative quantitative assessment of ecological resources in forest formations of the Volga River basin by specific and total values of their carbon balances under the predicted scenarios of climate changes. The ecological resources of two forest categories were assessed: primary and derivative. The main predictive climate scenarios were taken from E GISS Model, which gives the limits of climate changes corresponding to the purposes of the Paris Agreement. 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 (see Table 2 and Figure 4): in each of them, the total carbon balance [ $\sum \Delta C(Fa)$ ] approaches +190 million tons. The sub-taiga spruce and pine-broadleaf forests in the western sector of the basin have an almost equally high ecological resource, with [ $\sum \Delta C(Fa)$ ]  $\approx +140 \div 170$  million tons). The East-European broad-leaved forests are a striking contrast to the above-mentioned forest formations as they have a substantial negative effect on carbon exchange between the Earth’s surface and the atmosphere: here  $[\sum \Delta C(Fa)] > -100$  million tons.

The negative forest formations in the Oka-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 applies to both restored primary forests and real forest cover.

Table 2. 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.

Association groups (see Table 1)	Total area spare, sq. km	The total base 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)
<b>Sum (average)</b>	<b>845493</b>	<b>16043.828</b>	<b>+513.708 [+]</b> <b>+(11.31)</b>	<b>+797.319 [+]</b> <b>+(14.02)</b>

In other words, global warming should lead to the inevitable loss by both bioclimatic systems of the basin (potential and real) of ecological resources in mitigating climate fluctuations.

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, 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.

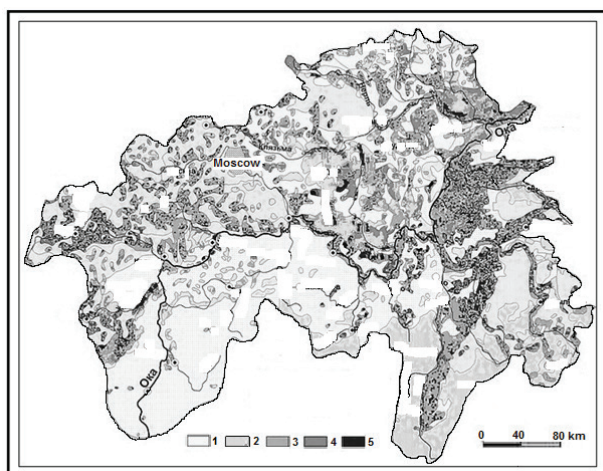


Figure 4. The distribution of the specific carbon balance in the restored primary forest associations of the Volga River basin for scenario of regional warming (2200), according to the E GISS model. Raster maps were calculated and compiled by L.S. Sharaya. Carbon balance (t / ha): 1 – (-15.0) ÷ (-7.5); 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.

As a result, the forest cover of the Oka-Volga River basin can acquire a mostly positive carbon balance under extreme warming (see Table 2 and Figure 5). For example, the East European sub-taiga broadleaf-spruce forests with weakly marked negative regulation of the carbon cycle ( $\Delta C(Fa) = -7.12$  tons/ha) according to the E-GISS warming scenario, become the subjects of substantial positive regulation ( $\Delta C(Fa) = +20.01$  tons/ha) at a stronger thermo-arid signal according to the HadCM3 model. Together with boreal (sub-taiga and taiga) forests, they are capable

of general positive regulation of the carbon cycle. General ly, we can state the total mitigating effect of forest cover of the basin on climate changes as the hydrothermal signal becomes more intensive.

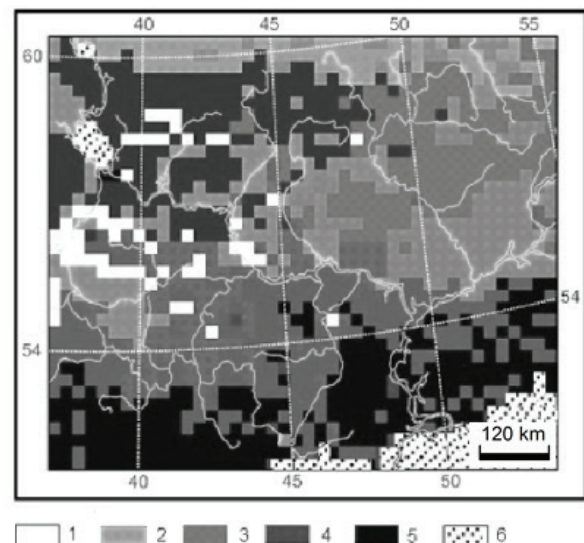


Figure 5. The distribution of the specific carbon balance (t / ha) of the restored primary forest associations of the Volga River basin for the extreme warming scenario, according to the HadCM3 model for a period of 2100. The raster map was calculated and compiled by L. S. Sharaya. Carbon balance (t / 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 regime of the region with extreme anthropogenic transformation. One of the three world centers of destabilization of the global environment, where a single space with completely disturbed forest cover of several million square kilometers has formed and where no more than 5–10% of natural ecosystems have survived (Losev, 2001). is the Volga Region and in particular its most anthropogenically altered part – the Oka River basin. In the system of zoning the territory of Russia by the severity of the ecological situation (Kochurov, 1992), the latter refers to territories with a catastrophic situation, where anthropogenic loads exceed standard values and ecological requirements. This has led to the depletion of natural resources, with a colossal loss of phytomass, as well as to a significant loss of the gene pool and unique natural objects (Losev, 2001).

The numerical experiment on assessment of the effect of labile elastic stability of forest formations and predicted climatic parameters on the carbon balance of forests, i.e., on their adsorption capacity, was carried out in collaboration with L.S. Sharaya in the territory of the Oka River basin (about 250 thousand km<sup>2</sup>).

It is necessary, first of all, to assess the contribution of separate groups of forest formations of the Oka River basin to the total biotic C cycle regulation. Multiple regression equations used for the construction of the maps are presented in Table 3. These equations were used for the construction of the maps of total carbon content in the forest formations and its changes under global warming. According to the HadCM3 prognostic model, the present-day forest cover of this region is, in general, expected to positively regulate the carbon cycle under the conditions of global climate warming. The regulation, however, will not be substantial. The prognostic map also reveals the sharply contrasting and small contour mosaic pattern of the positive and negative values of the carbon balance. The lower Oka–Moksha–Tsna right bank

meridional zone, which is mostly covered with complex pine forests and their small leaved forests, has an especially motley pattern, with  $\Delta Fa$  varying from +65–100 to –(80–136) t/ha. However, positive  $\Delta Fa$  values (0–40 t/ha) prevail.

The Ryazan Meshchera region, with its bog–pine forest woodlands on outwash plains, is another region with a positive carbon balance. Small negative  $\Delta Fa$  values (mainly between 0 and –12 t/ha and as low as –38 t/ha in some places) will be characteristic of the sub-boreal forests on lowland outwash plains in the left-bank part of the lower Klyaz'ma River basin and the neighboring right bank Volga River dominated by broadleaf–spruce and spruce–birch forests. Fragmentary forests on the vast territories of agricultural fields will implement for the most part feebly marked positive biotic regulation of the carbon cycle.

Table 3. Equations of the connections of carbon content change in forest formations of the Oka River basin to year of 2050 ( $\Delta C(Fa)_{2050}$ ) with most important environment factors.

Groups of plant associations	Regression equations
a) Spruce and broadleaf-spruce forests	$\Delta C(Fa)_{2050} = 76.7 \cdot Z + 46.7 \cdot T + 24.0 \cdot Q - 63.8$
b) Pine and broadleaf-pine forests	$\Delta C(Fa)_{2050} = -24.0 \cdot Z + 21.0 \cdot MCA - 7.1 \cdot Q + 12.1$
c) Broadleaf forests	$\Delta C(Fa)_{2050} = -76.2 \cdot T + 42.9 \cdot MCA + 12.1 \cdot GA + 5.1$
d) Secondary substituting for pine and broadleaf-pine forests	$\Delta C(Fa)_{2050} = 83.1 \cdot kmax + 76.6 \cdot MCA + 9.7 \cdot T - 61.6$
e) Secondary substituting for spruce, pine and broadleaf forests (all secondary forests of basin)	$\Delta C(Fa)_{2050} = 37.5 \cdot MCA - 18.4 \cdot GA - 10.9 \cdot T + 12.7$
f) Primary and secondary forests of basin (all basin forests on their contemporary areas)	$\Delta C(Fa)_{2050} = 28.8 \cdot MCA + 23.9 \cdot kmax - 7.2 \cdot T - 7.8$

Foot-note. Predictors in regression equations are: Z – elevation; MCA – maximal catchment areas; GA – gradient (degrees) of the slopes; kmax – ridge geometrical forms; Q – insolation (instant intensity of direct solar irradiation); T – average temperature of July.

Table 4. Change of summary carbon supplies (millions of thons) in plant formations of Oka River basin to 2050, by HadCM3 model.

Forests (groups of plant associations)	Aria, km <sup>2</sup>	Base summary carbon	Change of the carbon content			
			deposit	emis-sion	Common sum	
					millions	%
1. Spruce and broad-leaf/spruce mixed	2034	37.14	3.02	–1.8	1.22	3.28
2. Pine and broadleaf-pine mixed	26230	481.76	45.77	–23.17	22.6	4.69
3. Broadleaf	4770	84.68	6.76	–4.96	1.8	2.13
4. Secondary substituting for dark-co-niferous and mixed	17770	293.26	40.77	–14.79	25.98	8.86
5. Secondary substituting for light-co-niferous and mixed	16670	318.7	40.97	–51	–10.03	–3.15

6. Secondary substituting for broadleaf	4911	76.83	0.42	–1.18	–0.76	–0.99
7. Swampy	2343	35.18	1.01	–0.17	0.84	2.39
8. Flood-plain	9219	149.28	6.62	–4.45	2.17	1.45
All groups of forest for-mations	83947	1476.83	145.34	–101.52	43.82	2.97

Toward the solution of the dual problem of absorption and adaptation. As already stated, one of the most important pathways for implementation of the objectives stipulat-ed in the Paris (2015) Agreement on Climate Changes is the solution of the dual problem: adsorption of atmospheric CO<sub>2</sub> by forest communities from the atmosphere under global warming and their adaptation to these climate changes, which must provide the efficiency of adsorption per se. Labile plastic-elastic resilience of forest ecosystems was considered as an indicator of adaptation.

The numerical experiment on assessment of the effect of labile elastic stability of forest formations and predicted climatic parameters on the carbon balance of forests, i.e., on their adsorption capacity, was carried out in collaboration with L.S. Sharaya in the territory of the Oka River basin (Table 5). 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. Thereby, 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 (Shary et al., 2002), 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,  $\Delta C(Fa)$  is the change in the specific flow of CO<sub>2</sub> (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 pre-cipitation;  $R_s$  is the Spearman's rank correlation coefficient. The generally low values of this coefficient are determined by the enormous number of statistical samples (see above) with a substantial “noise” of local geomorphological and edaphic factors forming the groups of mean values with opposite connections. Nevertheless, the general tendency of connections can be considered quite reliable for each equation, as is evidenced by a sig-nificant Pearson's correlation coefficient P.

Each zonal/sub-zonal type/sub-type includes primary and derived forest communities, as well as fragmented timberlands, i.e., represents the state of real forest cover.

Equations derived are proposed to be included directly in the “Guidelines for the quanti-tative 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 0.2–0.60 in winter to 0.8–1.10 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 2.5–4.00 for this period, which can occur at the current rates of global warming (Le Quéré et al., 2015; Shvidenko et al., 2017).

The results of the calculation of  $\Delta C(Fa)$  are quite similar to the data obtained by other methods (Kolomyts, 2022), though there are some differences. According to the climate scenario for 2100 based on the HadCM3 prediction model, there is almost the same average specific carbon balance of forest cover in both cases (11.05 and 10.02 tons/ha·yr, re-spectively). The maximum adsorption capacity is due to sub-taiga forest formations; however, it is 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 2). The comparison of values of the carbon 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 do not take into account the changes in ecological resources of forest formations, which are caused by their functional and structural trans-formations throughout the given prediction period. These changes are ambiguous. According to the climate scenarios of moderate warming (GISS-93 and E GISS), algebraic addition of the  $\Delta C(Fa)$  values has been made for the zonal/sub-zonal types/sub-types of forest formations of the Oka River basin (see Tables 5). The following indices of changes in the specific carbon balance of forests [ $\Delta C(Fa)$ ] have been obtained (tons/ha): A (+4.998); B (–14.570); C (+27.773); D1 (+10.010). Generally, the ecological resources of the entire repertoire of boreal dark-coniferous and dark-coniferous/broadleaf, as well as sub-taiga broadleaf-pine forests, are preserved. The adsorption capacity of broad-leaved forests also noticeably increases (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 lose their ecological resources, though their  $\Delta C(Fa)$  remains positive.

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 sub-types of forest associations (see Table 1)	Weighted average index of resilient stability, <i>Iresili</i> (1)			Climatic parameters projected for 2100				Specific carbon balance, t/ha		Wooded area, km <sup>2</sup>	Total carbon balance, million tons	
	Base	Projected		GISS-93 model		HadCM3 model		Model GISS-93	Model Had-CM3		Model GISS-93	Model HadCM3
		GISS-93 model	Had-CM3 model	<i>t</i> <sub>July</sub> , °C	<i>r</i> <sub>year</sub> , mm	<i>t</i> <sub>July</sub> , °C	<i>r</i> <sub>year</sub> , mm					
A. Spruce and broadleaf-spruce forests, taiga and sub-taiga	0.554	0.630	0.670	20.1	950	22.2	725	9.70	8.87	75'706	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	12.82	48'506	44.771 29.249	62.185 43.170
C. Broadleaf-pine forests, sub-taiga	0.531	0.664	0.684	21.6	830	23.0	705	18.70 57.83	44.51 82.76	37'841	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	18'350	–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	7'544	– 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	7'052	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	16'267	5.482 5.092	7.676 18.871
<b>Weighted average / Sum</b>	<b>0.517</b>	<b>0.634</b>	<b>0.673</b>	<b>20.4</b>	<b>921</b>	<b>21.0</b>	<b>717</b>	<b>3.61 11.62</b>	<b>10.02 17.10</b>	<b>211'266</b>	<b>179.376 354.091</b>	<b>284.281 486.012</b>

Foot-note: *t*<sub>July</sub> is the average temperature in July; *r*<sub>year</sub> 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.

The presented data indicate, altogether even more clearly than it has been shown previously, the phenomenon of increasing adsorption capacity of forest cover of the Oka-Volga River basin with the intensification of the global warming signal and the respective increase in elastic-plastic resilience of ecosystems. It can also be verified by a comparison of  $\Delta C(Fa)$  values from the GISS-93 and HadCM3 models (see Tables 5). The increase in forest-restoration adaptation, being a direct ecological factor, makes a decisive contribution to the enhanced adsorption of greenhouse gases.

Let us consider the denoted regularities in more detail with regard to the equations presented above. For all formations of the Oka River basin as a single group (equation E) it has been shown that their carbon balance has a positive relationship with the restoration potential and the major climatic parameters. At the temperature and precipitation close to the average values, carbon deposit becomes more intensive with the increasing index of elastic resilience, while CO<sub>2</sub> emission intensifies as the latter decreases. However, the general tendencies toward the changes in temperature and precipitation on the territory of the basin can be approximately characterized as opposite, especially in the southeastern direction (by 26000 points of forest ecosystems, the Spearman's rank correlation coefficient RS for tJuly and rann is  $-0.92$ ,  $P < 10^{-6}$ ). If such a compensatory ratio is maintained, only the decrease in restoration potential can be responsible for the negative carbon balance. The carbon balance close to the equilibrium state is associated with different values of elastic resilience on the territory of the basin. For example, it is  $I_{stab}(i) = 0.418$  for the central areas of the Oka River basin,  $0.465$  for its northwestern area, and  $0.385$  for the drier and warmer southeastern area. If the restoration potential takes lower values, the carbon balance becomes negative. It means that forest formations more resistant to global warming have altogether higher adsorption capacity.

Such dependence is also typical of the group combining all derivative forests (equation H). Here, however, the restoration potential has a greater weight, and the dependence of carbon balance on annual precipitation is more marked than the dependence on the mean July temperature. In essence, it can imply a more rapid reduction of the adsorption capacity of secondary forests with the decrease in their resilience and in annual precipitation.

The carbon balance of primary forests as a single group in the Oka River basin is positively related to temperature and precipitation and negatively related to the elastic resilience of forest formations (equation G). Here, the elastic-plastic resilience of forests has a very low relative weight. It can be due to the absence in all primary forests of unambiguous dependence between their carbon balance and restoration potential. A positive relationship has been revealed for spruce and broadleaf-spruce, broadleaf-pine, northern broadleaf forests; the negative relationship has been shown for pine south-taiga and broadleaf forests of more southern latitudes. In the latter cases, the deposit will be highly dependent on precipitation, with its decrease resulting in the negative carbon balance. Let us also note that emissions in the primary and derived forests of the southern forest-steppe and northern steppe can be maintained by the relatively high restoration potential of these forests.

## Conclusion

The carried out analytical modeling of changes in the carbon balances of forest formations of the Oka-Volga River basin, depending on their elastic-plastic stability, sheds some light on the dual problem posed by the Paris Agreement, on the need for

a coupled study of the adsorption capacity of forest biomes and their adaptation to a changing climate.

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## Conflict of Interest

Author declares no conflicts of interest in this paper.

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