RESEARCH ARTICLE

Ecological resources of boreal forests in the adsorption of greenhouse gases and in adaptation to global warming

Erland G. Kolomyts

Institute of Basic Biological Problems, Russian Academy of Sciences, Pushchino, Russia

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_2 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 isomorphic-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

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 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 [4, 5], 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" [6].

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 [7] . 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 techno-genic greenhouse gas emissions to the atmosphere suggests an increase in the mean global temperature of the Earth's surface within 1.4–5.8^{o}C over the period from 1990 to 2100, which is 2–10 times above the magnitude of warming that occurred in the XX century [8] . 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 [9] . At the same time, regional warming in the territory of Russia can be on the order of $6–11^o$ [10] .

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 [11] . Following the Paris Climate Change Agreement, *measures should be taken for the warming to be no more than* 1.5-2.0^oC *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 [10] 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.

2   Ideological foundations

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 [12–14]]. 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 [13] , *i.e.*, the leading "ecosystem services" of forest cover [15]. 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* [14, 16]. This is essentially about the need to switch to adaptive forestry, taking into account the special sensitivity of forests to "rapid" climate changes [16] , to ensure the adaptation of forests to global changes and their use to mitigate unwanted climate changes [17] .

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 [18] . We will consider the dual problem of ecological resources of forest ecosystems: on the one hand, their "work" on additional adsorption/emission of CO_2 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 [12, 13] 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 [14] . At the same time, almost half of them are boreal forests providing more than 90% of the carbon sink of all boreal forests worldwide [16] . 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 [19] . 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 [13] . 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   Materials and methods

The experiment used the materials of large-scale landscape-ecological surveys carried out earlier using a specially developed technique at five experimental test sites of the Middle and Upper Volga regions [20] . Each test site characterized a specific ecoregion with its groups of plant formations (Figure 1; Table 1).

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 extrapolation*, which has been described detail in the work [21] . The method is based on the above-mentioned property of polyzonality of local ecosystems. The advantage of this method is that is uses directly the data of large-scale landscape-ecological surveys.

Next phytomass parameters (tons/ha) have been used for calculation of carbon balance: (1) skeletal tree-shrub phytomass, *BS;* (2) root mass, *BR;* (3) total verdure mass, *BV;* (4) forest litter mass, *ML;* (5) debris – dead skeletal mass (brushwood and dead-wood), *WD;* (6) humus mass in organic-mineral layers of the soil, *HU.* Live phytomass were calculated by the general and regional tables of biological productivity of fully stocked (normal) stands [22] 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 [23–25].

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 topoecosystems (biogeocoenoses, or facies) 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: 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 parameters.

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, $P < 0.05$). The R^2 values ranged from 65–75% to 25–35% (Figure 2). 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.

Table 1   Classification scheme of indigenous and derived plant formations of the main drainage area of the Oka-Volga River basin and its surroundings, after [26]. Legend for the forest map (see Figure 1)

Zonal types and sub-types of the formations	Groups of plant formations
Dark coniferous and broad-leaved-dark coniferous forests (derivatives of aspen-birch)	Middle and southern taiga spruce forests and broadleaf-spruce sub-taiga forests, southern taiga fir-spruce and broadleaf fir-spruce subtaiga forests
Pune forests	Middle and southern taiga pine forests Middle and southern taiga pine forests with an admixture of larch
Broadleaf-pine forests (derived from aspen and birch)	Broadleaf-pine sub-taiga forests Eastern European forest-steppe and steppe pine forests
Broadleaf forests (derived from aspen and birch)	Broadleaf oak and linden-oak from pedunculate oak with an admixture of other broadleaf forest species, and broadleaf linden trees with an admixture of other broad-leaf forest species
Intrazonal plant formations	Sphagnum southern taiga and subtaiga raised bogs, pine-dwarf shrub-sphagnum Willow forests, swampy, with deciduous and dark coniferous species; nemoral floodplains with willow, black alder, elm, willow, sedge and oak forests
Birch and aspen forests in the place of	southern taiga fir-spruce forests middle – and south-taiga pine forests sub-taiga fir-spruce forests sub-taiga pine forests forest-steppe and steppe pine forests
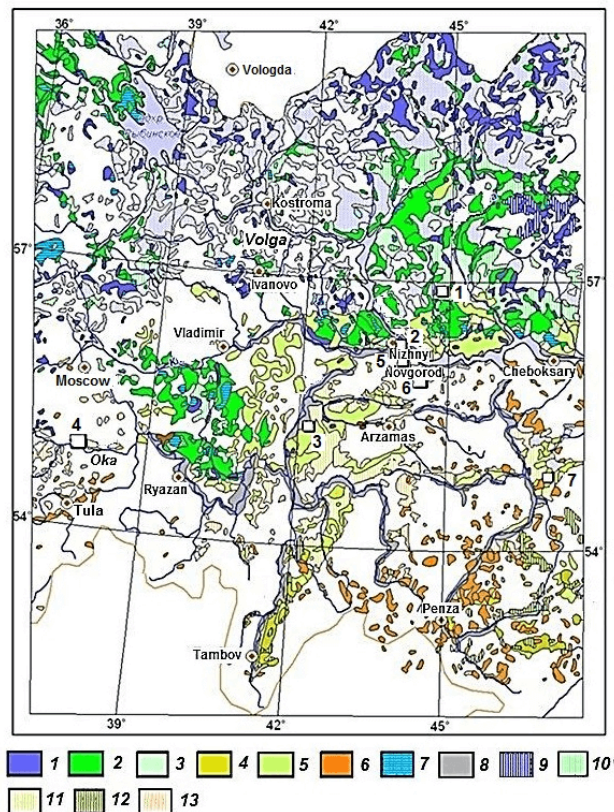
Notes: 1–13: convention meanings of plant formations see in the Table 1. 1–7: test site numbers (explanation in the text).

Figure 1   The plant cover of the Middle Volga Region, and the layout of experimental test sites [26].

As is known [27] , 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. 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 contents of individual biotic components and forest biogeocoenoses in general, we used the traditional forest management method [1, 23] 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.
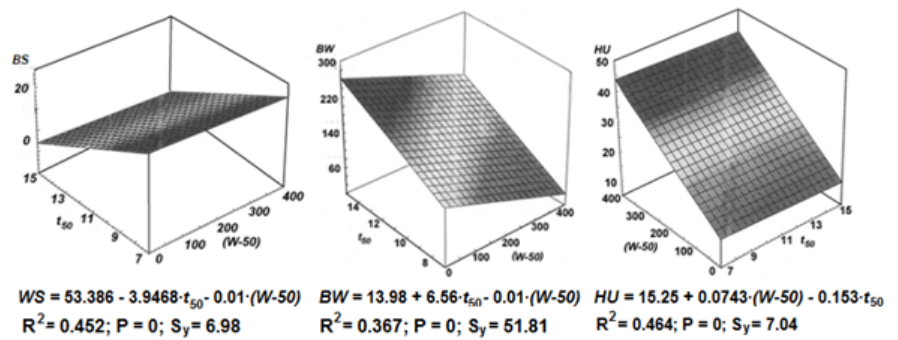
$$WS = 53.386 - 3.9468 \cdot t_{50} - 0.01 \cdot (W-50) \qquad BW = 13.98 + 6.56 \cdot t_{50} - 0.01 \cdot (W-50) \qquad HU = 15.25 + 0.0743 \cdot (W-50) - 0.153 \cdot t_{50}$$
$$R^2 = 0.452; P = 0; S_y = 6.98 \qquad R^2 = 0.367; P = 0; S_y = 51.81 \qquad R^2 = 0.464; P = 0; S_y = 7.04$$

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).

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 [28, 29]: 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 I*stab(*i*) of *i*-th ecosystem:

$$Istab(i) = 1 - \left[\sqrt{(\Delta R_i)^2 + (\Delta Y_i)^2} \right] \Big/ \sqrt{2} \qquad (3)$$

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_i approaches CR_{max} and CY_i approaches 0, then *I*stab(*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 [20] :

$$Istab(i) = 0.7150.0555 \times CY; \;\; R^2 = 0.90 \tag{4}$$

$$CY = 0.993 \times t_{\text{Janv}} - 0.5365 \times t_{\text{July}} + 0.003508 \times r_{\text{ann}}; \;\; R^2 = 0.61 \tag{5}$$

$$CY = exp(6.453 - 0.2993 \times t_{\text{July}}); \;\; R^2 = 0.76 \tag{6}$$

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

The analysis of the sustainability of the forest cover of the Oka River basin was carried out for its water management areas (WEA), which was associated with the well-known hydro-ecological role of the forest [1, 30]. According to the Water Code of Russia, the water management area is a part of the river basin, which has characteristics that make it possible to set limits for the intake of water resources from a water body and other parameters of water use. To determine the areas occupied by forests in the WEA of the Oka River basin, satellite data [31] were used, which were obtained from the SPOT4-VEGETATION apparatus and processed within the framework of the GLC 2000 project of the Joint Center of the European Commission (Global Land Cover). These materials are located on the website of the Space Research Institute of the Russian Academy of Sciences http://terranorte.iki.rssi.ru.
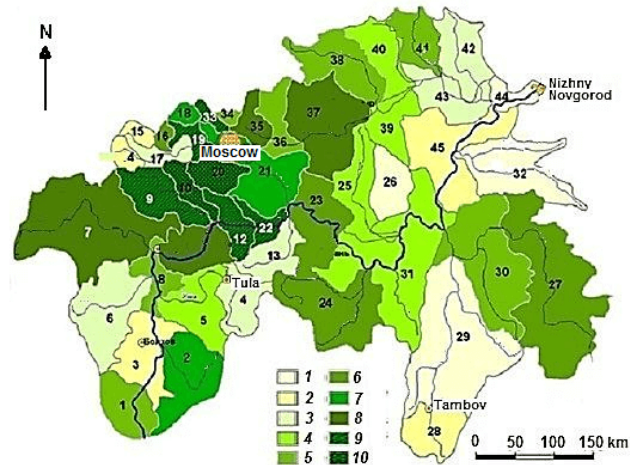
Notes: 1–45 are the numbers of water supply areas. Indices of the Istab(i) parameter: 1: 0.40–0.491; 2: 0.491–0.506; 3: 0.506–0.516; 4: 0.516–0.531; 5: 0.531–0.549; 6: 0.549–0.563; 7: 0.563–0.569; 8: 0.569–0.597; 9: 0.597–0.652; 10: 0.652–0.654.

Figure 3 Average values of the indices of elastic-plastic stability of forest formations of the Oka basin (for water-economic areas)

On the map of the Oka River basin, as a whole, there are three bands of prevailing values of taxonomic norms of elastic-plastic stability of forest ecosystems (Figure 3). The bands are directed sub-latitudinally – 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 Smolensk-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 (re-gions 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. However, even in this zone, forest formations have a sufficiently developed capacity for restorative successions. The third sub-latitudinal 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 basin and the main elements of the plain relief. Low values of Ifr are characteristic of both the northern part of the Central Russian Upland and the Oka-Don Lowland.

The quantitative approaches to prognostic ecological and geobotanical mapping recently developed abroad [32] 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 mapping 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 [33, 34] for drawing spatiotemporal maps.

The procedure of regional mapping was performed using the vegetation maps for the European part of the former USSR at the above-mentioned scales compiled in the 70s–80s of the last century [35, 36], *i.e.*, approximately at eth 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 [37] , 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 [38] , 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 European or Kama-Pechora) of the types and sub-types of plants – middle taiga, sourhern 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 [3] 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 [3, 31], 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 [2] . Such forest categories do not at all correspond to the meaningful meaning of the concepts of "classes of plant formations" and "types of vegetation" [38] accepted in traditional geobotany [36].

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 biogeocenoses 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 [39] , with her earlier version GISS-93, and 2) extreme HadCM3 model, Version A2 [40] . 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 $-0.5 \div 1.9^o$ 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 [20] . 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 sub-continent over the next 100–200 years.

4   Results and discussion

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^2).

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 (Figure 3). Multiple regression equations used for the construction of the maps are presented in Table 2. These equations were used for the construction of the maps of total carbon content in the forest formations and its changes under global warming (Figure 4; Table 3). 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 ΔFa varying from +65–100 to –(80–136) t/ha. However, positive ΔFa values (0–40 t/ha) prevail.

Table 2 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 formations	Regression equations
Spruce and broadleaf-spruce forests	$\Delta C(Fa)_{2050} = 76.7\ Z + 46.7\ T + 24.0\ Q - 63.8$
Pine and broadleaf-pine forests	$\Delta C(Fa)_{2050} = -24.0\ Z + 21.0\ MCA - 7.1\ Q + 12.1$
Broadleaf forests	$\Delta C(Fa)_{2050} = -76.2\ T + 42.9\ MCA + 12.1\ GA + 5.1$
Secondary substituting for pine and broadleaf-pine forests	$\Delta C(Fa)_{2050} = 83.1\ k_{max} + 76.6\ MCA + 9.7\ T - 61.6$
Secondary substituting for spruce, pine and broadleaf forests (all secondary forests of basin)	$\Delta C(Fa)_{2050} = 37.5\ MCA - 18.4\ GA - 10.9\ T + 12.7$
Primary and secondary forests of basin (all basin forests on their contemporary areas)	$\Delta C(Fa)_{2050} = 28.8\ MCA + 23.9\ k_{max} - 7.2\ T - 7.8$

Notes: Predictors in regression equations are: Z – elevation; MCA – maximal catchment areas; GA – gradient (degrees) of the slopes; k_{max} – ridge geometrical forms; Q – insolation (instant intensivity of direct solar irradiation); T – average temperature of July.

The Ryazan Meshchera region, with its bog–pine forest woodlands on outwash plains, is another region with a positive carbon balance. Small negative ΔFa 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 Change of summary carbon supplies (millions of thons) in plant formations of Oka River basin to 2050, by HadCM3 model

Forests (groups of plant formations)	Area (km^2))	Base summary carbon	Change of the carbon content			
			deposit	emission	Common sum	
					millions of thons	%
1. Spruce and broadleaf/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-coniferous and mixed	17770	293.26	40.77	-14.79	25.98	8.86
5. Secondary substituting for light-coniferous 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 formations	83947	1476.83	145.34	-101.52	43.82	2.97

Turn directly to the results of our regional experience in solving the two-pronged 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. Thereby, an array of cartographic data was formed (more than 52 000 points). The spatial variability of the carbon
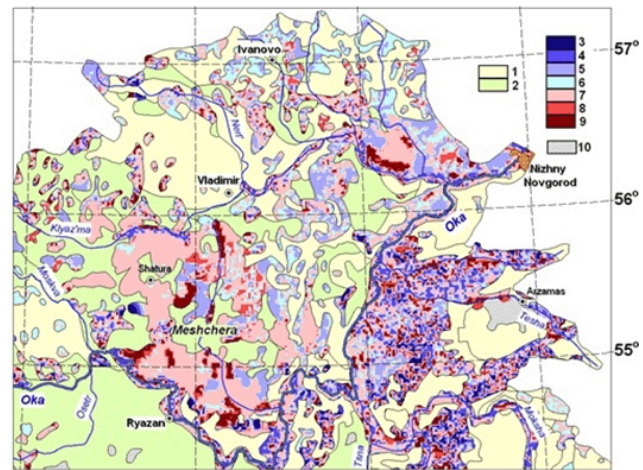
Notes: The changes in total C stocks for the predicted period of 2050 relative to the base period (t/ha): 1: (-1.3)÷0; 2: 0 ÷5.5; 3: (-136)÷(-25); 4: (-25)÷0; 5: 0÷25; 6: 25÷115. 1, 2: fragmentary huge tracts of forest among agricultural fields. 3-6: forest arias. 10: the northern area of steppes.

Figure 4   Map of predictive changes of total carbon content on the territory of Oka River basin by HadCM3 model.

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 [33] , and some satellite data on the characteristics of forests (vegetation index NDVI, crown closure).

Table 4   Equations of the connections of carbon content change in forest formations of the Oka River basin with their plastic-elastic functional stability and the climate characteristics

Plant formations	Regression equations	Statistic	
		R_s	P
A. Spruce and broadleaf-spruce forests; middle- and south-taiga and sub-taiga	$\Delta C(F_a) = 62.4\ I\text{stab}(i) + 22.7\ r_{\text{ann}} + 10.2\ t_{\text{Jul}} - 49.3$	0.50	$< 10^{-6}$
B. Pine south-taiga forests	$\Delta C(F_a) = 38.6\ r_{\text{year}} + 29.4\ t_{\text{Jul}} - 16.0\ I\text{stab}(i) - 24.8$	0.46	$< 10^{-6}$
C. Broadleaf-pine forests, sub-taiga	$\Delta C(F_a) = 217.4\ I\text{stab}(i) + 78.0\ t_{\text{Jul}} + 55.3\ r_{\text{ann}} - 165.6$	0.64	$< 10^{-6}$
D_1. Northern broadleaf forests, with an admixture of spruce	$\Delta C(F_a) = 6.23\ I\text{stab}(i) - 4.65\ t_{\text{Jul}} + 4.30\ r_{\text{annr}} - 5.63$	0.46	$< 10^{-6}$
D_2. Southern steppified broadleaf forests	$\Delta C(F_a) = 32.9\ t_{\text{Jul}} + 24.1\ r_{\text{year}} - 54.3\ I\text{stab}(i) - 19.6$	0.38	$< 10^{-6}$
E. All formations of the Oka River basin	$\Delta C(F_a) = 76.3\ I\text{stab}(i) + 36.9\ t_{\text{Jul}} + 31.1\ r_{\text{ann}} - 69.6$	0.13	$< 10^{-6}$
G. All formations of primary forests	$\Delta C(F_a) = 68.6\ t_{\text{Jul}} + 37.1\ r_{\text{ann}} - 3.4\ I\text{stab}(i) - 51.0$	0.16	$< 10^{-6}$
H. All formations of secondary forests	$\Delta C(F_a) = 123.5\ I\text{stab}(i) + 22.8\ r_{\text{ann}} + 18.7\ t_{\text{Jul}} - 64.6$	0.30	$< 10^{-6}$
I. Secondary forests in place of pine	$\Delta C(F_a) = 2218\ I\text{stab}(i) - 68.5\ t_{\text{Jul}} + 33.9\ r_{\text{ann}} - 83.2$	0.45	$< 10^{-6}$
K. Secondary forests in place of broadleaf	$\Delta C(F_a) = 10.7\ I\text{stab}(i) + 6.0\ r_{\text{year}} - 4.6\ t_{\text{Jul}} - 12.2$	0.13	$< 10^{-6}$
L. Forests of the southern forest-steppe and northern steppe	$\Delta C(F_a) = 95.4\ t_{\text{Jul}} - 78.3\ I\text{stab}(i) + 47.5\ r_{\text{ann}} - 22.6$	0/54	$< 10^{-6}$

The resultant functional relationships between the carbon balance and the adaptation for zonal/sub-zonal types/sub-types of forest formations are given below in Table 4. Here, $\Delta C(F_a)$ is the change in the specific flow of CO_2(tons/ha·year) in the terrestrial surface–atmosphere system; $I\text{stab}(i)$ 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 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 significant 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 derivedare 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 5 shows the results of calculations (by formulas in Table 4) 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_{year} 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^o in winter to 0.8–1.1^o 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^o for this period, which can occur at the current rates of global warming [9, 10].

The results of the calculation of ΔC(Fa) are quite similar to the data obtained by other methods [41] , 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, respectively). The maximum adsorption capacity is due to sub-taiga forest formations; how- ever, 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 4). 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 transformations 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 ΔC(Fa) values has been made for the zonal/sub-zonal types/sub-types of forest formations of 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 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 ΔC(Fa) remains positive.

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 ΔC(Fa) values from the GISS-93 and HadCM3 models (see Table 5). The increase in forest-restoration adaptation, being a direct ecological factor, makes a decisive contribution to the enhanced adsorption of greenhouse gases.

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_2 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 R_S for t_{July} and r_{year} 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 Istab(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

Table 5　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 (see Table 1)	Weighter average index of resilient stability, I resili(1)			Climatic parameters projected for 2100				Specific carbon balance, t/ha		Wooded area, km²	Total carbon balance, million tons	
	Base	Projected		GISS-93 model		HadCM3 model		Model GISS-93	Model HadCM3		Model GISS-93	Model HadCM3
		GISS-93 Model	HadCM3 Model	t_{July}, °C	r_{year}, mm	t_{July}, °C	r_{year}, mm					
A. Spruce and broadleaf-spruce forests, taiga and sub-taiga	0.554	0.63	0.67	20.1	950	22.2	725	9.7	8.87	75'706	73.435	67.151
								14.44	16.04		109.319	121.432
B. Pine south-taiga forests	0.43	0.63	0.675	20.1	930	22.6	710	9.23	12.82	48'506	44.771	62.185
								6.03	8.9		29.249	43.170
C. Broadleaf-pine forests, sub-taiga	0.531	0.664	0.684	21.6	830	23	705	18.7	44.51	37'841	70.763	160.430
								57.83	82.76		218.835	313.172
D_1. Northern broadleaf forests, with an admixture of spruce	0.547	0.667	0.689	22.2	780	23.8	685	− 5.58	− 5.26	18'350	−10.239	−9.652
								− 2.32	− 3.61		−4.257	−6.624
D_2. Southern steppified broadleaf forests	0.547	0.667	0.689	23.8	700	24	650	−14.00	− 10.83	7'544	− 10.562	− 8.170
								− 17.86	− 18.57		−13.434	−14.009
Waterlogged coniferous forests and forest swamps	0.549	0.63	0.672	20.1	940	22.4	720	8.12	6.61	7'052	5.726	4.661
								13.17	14.18		9.287	10.000
Nemoral floodplains	0.559	0.642	0.685	22.5	770	23.6	680	3.37	4.69	16'267	5.482	7.676
								3.13	11.53		5.092	18.871
Weighted average / Sum	0.517	0.634	0.673	20.4	921	21	717	3.61	10.02	211'266	179.376	284.281
								11.62	17.1		354.091	486.012

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.

5　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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