Estimation forecast of the Russian Federation forests carbon balance based on the long-term scenarios of forest complex development

I O Torzhkov¹, A V Konstantinov¹,² and E A Kushnir¹

¹ Research Department for Forest Ecosystem Monitoring, SPbFRI (Saint Petersburg Forestry Research Institute), No. 21, Institutsky Pr., St. Petersburg, 194021, Russia
² Department of Dynamic Meteorology and Climatology, Federal State Budgetary Institution “The Voeikov Main Geophysical Observatory” (named after A.I. Voeikov), No. 7, Karbysheva St., St. Petersburg 194024, Russian Federation
¹E-mail: fin@spb-nilh.ru

Abstract. The study assessed the carbon balance of the forests in Russia according to long-term plans for the economic development of the forest sector until 2050, taking into account the expected climate changes. The calculated data of the regional climate model for the IPCC (Intergovernmental Panel on Climate Change) RCP-8.5 plan to assess the impact of changes in physical abiotic factors on the forest ecosystems were used in the work. Two key parameters were taken into account in calculations that could be affected by expected climate change that are forest fires and plant productivity. The forecast is carried out according to three scenarios for the development of the forest complex of Russia: inertial, basic and strategic. The overall carbon balance of Russia is expected to be at the level of 187.5-251.2 MtC per year, depending on the scenarios of forest management and growth of forests productivity, these data accord the current values. Maintaining a positive carbon balance in forests will require the development of measures to improve fire control in forestry, timber technologies and reforestation.

1. Introduction
The scientific community has a conception of the need to consider climate change when modeling the development of biological and socio-economic systems. Sustainable forest management is necessary both for the absorption and storage of carbon, and for maintaining maximum forest productivity in the long term, including methods for maintaining and eliminating risks from potential damage from natural fires, pests, diseases and extreme weather conditions, as well as maintaining biodiversity. The benefits of reducing emissions from forest conservation and strengthening activities and minimizing potential negative impacts need to be maximized [1].

Domestic and foreign researchers have developed the models for predicting carbon balance changes of varying degrees of accuracy, which take into account many factors. Experts on climate change believe that reforestation and afforestation are effective measures to remove excess CO₂ from the atmosphere and retain carbon [2, 3]. However, the existing forecasts do not consider the change in ecosystems themselves due to the observed climate changes, which are a possible decrease or increase in the productivity of plantations, fire control, an increase of insect pests and forest diseases, and an increase the number of extreme weather conditions. The current forecasts for the development of economic sectors do not sufficiently cover the planning of activities aimed at reducing greenhouse gas
emissions and increasing carbon sinks. During the preparation of the next long-term forecast for the development of the forest economy sector, it is necessary to take into account the expected effects of climate change.

2. The problem statement
The aim of the study is to assess the wood reserves in the Russian Federation for the middle of the century, according to wood harvesting plans, which are established in the Strategy for the Development of the Forestry Complex of the Russian Federation until 2030, and also the forecast of carbon balance due to possible changes in the productivity of forest plantations and fire control for the period until 2050. The random of the dynamics of climate change and the extent of their impact on forest ecosystems remains the scientific problem. The main stages of work are forecasting the volume of wood removal in the Russian Federation as a result of logging, modeling changes in fire control and productivity of forest plantations, taking into account the growth of solar radiation, summing up the carbon balance with considering the calculated forecast options.

3. Methods and Materials
To assess the impact of changes in physical abiotic factors on forest ecosystems in the course of the study, a regional climate model (RCM) was developed, which was developed by the scientists of the Voeikov Main Geophysical Observatory plan - RCP-8.5 IPCC [4] with a forecast level of 2050–2059 [5]. The ensemble average of climate changes was used for the outline above.

As the calculations basis was taken the previously developed method for predicting the length of the growing season and the predicted change in the number of days with fire hazard classes II-V of the integrated fire hazard indicator of V.G. Nesterov and the change of the moisture index in the regions of Russia in accordance with the outlines RCP-4.5 and RCP – 8.5 [6]. In this work, based on current data on the positive correlation of plant productivity and the accumulated amount of active temperatures [7], the wood stocks were recalculated by 2050–2059.

The wood harvesting forecast until 2050 was calculated by extrapolation using the three outlines laid down in the Strategy for the Development of the Forestry Complex of the Russian Federation until 2030 [8] which are the inertial, basic and strategic.

The CBM-CFS3 model was used in the study, as the baseline forecast for the carbon balance of forests in Russia, without taking into account the effects of climate change, according to two of forest management outlines obtained by the authors, which are moderate growth and rapid growth.

To calculate the forecasted emissions in forestry due to various reasons of the wood removal, the averaged data presented by Zamolodchikov [9] were used: an increase in wood harvesting in the forests of Russia by 1 million m\(^3\) per year, which leads to carbon sink decrease by 0.20 MtC per year in all pools.

The assessment of greenhouse gas emissions from forest fires was carried out in two stages.

At the first stage, based on forecast meteorological information obtained previously on the change in the number of days of fire control in forestry due to climate changes [6], the expected area of forest fires was calculated. To predict the area of forest fires arising from climate change, in the middle of the century, the formula proposed by B. G. Sherstyukov and A. B. Sherstyukov was used [10] (1):

\[
S = S_q ^ 4
\]

where S is the area of forest fires, ha.
S\(q\) - index of forest area covered by fires

This model describes the dependence of the index of forest area covered by fires on the number of fire-dangerous days according to the V.G. Nesterov’s index. Comparing data on the area of forest fires for the period 1986-2004 [11] and the number of fire-dangerous days of III-V class in the territory of the Moscow region for the period 1986-2004 [11], the authors of this study had developed an
exponential model (figure 1). The advantage of the model could be considered a correct description of
the correlation of the number of days of fire danger and the area of forest fires, both at an early stage
and at points of extremum. With the increase in the number of days of fire danger, the area of fires
increases many times. The model is described by the formula (2):

\[ S = (0.9353 \times e^{0.0174x})^4 \]  

where S is the area of forest fires;
e is the Euler number;
x is the number of days of III-V classes of fire danger according to the V.G. Nesterov’s index.

Figure 1. The dependence of the forest area index covered by fires on the number of fire-dangerous
days according to V.G. Nesterov’s index in accordance with the exponential model.

At the second stage, the emissions forecast of the expected increase in the forest fires area was
carried out.

An increase in the area of forest fires with an increase in the number of days of fire danger
increases exponentially, in accordance with this the predicted calculation of greenhouse gas emissions
was made by increasing the current average level of fire danger in Russia by the forecast change
obtained in the study [6]. Formula 1 was applied to the received value on the number of days of fire
danger; as a result, the expected area of forest fires by 2050–2059 was calculated.

Estimated greenhouse gas emissions from forest fires were calculated based on the average
greenhouse gas emissions per 1 hectare of forest fires based on the area of forest fires and the amount
of greenhouse gas emissions from them for the period 1990-2016, presented in the National Report
inventory of anthropogenic emissions from sources and removals by sinks of greenhouse gases not
controlled by the Montreal Protocol [12].

4. Results and Discussion
The development strategy of the Russian Federation forest complex until 2030 [8] provides three
outlines for the forestry development which are inertial, basic and strategic. The inertial outline
assumes the absence or partial realization of sectoral investment projects and measures of state support
for the forest complex. According to baseline outline, it is planned to implement all the measures and
support measures stipulated by the Strategy for the Development of the Forestry Complex of the
Russian Federation until 2030 [8]. The strategic outline, in addition to the baseline, involves the
implementation of investment projects, minimizing risks and the accompanying favorable economic
conditions in export markets. In all scenarios, it is planned to increase the volume of forest use: up to 230.5 million m³ (inertial), 261.8 million m³ (base), 286.1 million m³ (strategic), which exceeds the 2017 logging level (212.4 million m³) by 8.5%, 23.0% and 34.7% respectively.

Potentially, the maximum level of timber cutting can be considered 100% of the volume of the annual cutting area, which is 703.0 million m³ as of 2016. However, these data do not take into account the accessibility of forest areas and the economic feasibility of forest use. According to FAO estimates, 45% of the forest area is available for operation, i.e. 532.8 million m³. The limiting indicators of logging can be retrospective data on the maximum volumes of production, which in 1975 amounted to 367.0 million dense m³, which amounts to ≈582.5 million m³ of production with a stacked-volume ratio of 0.63, i.e. ≈80% of the current annual cutting area.

An increase in the intensity and/or extensiveness of forest use may entail a change in the carbon balance.

The estimated volume of forest use was calculated according to three forest management scenarios by 2050, extrapolating the rate of increase in logging stipulated by the Strategy for the Development of the Forestry Complex of the Russian Federation until 2030. The calculation results were used to determine the volume of wood harvesting by 2050 according to the following scenarios (figure 2):

- base (241.1 million m³ per year);
- inertial (331.8 million m³ per year);
- strategic (437.5 million m³ per year).

Provided that an increase of 1 million m³ per year in wood harvesting in the forests of Russia leads to a decrease in carbon sink by 0.20 MtC per year, indicators for reducing the carbon balance due to forest use under the three outlines by 2050 were determined for all pools:

- base (48.2 MtC per year);
- inertial (66.4 MtC per year);
- strategic (87.5 MtC per year).

The Strategy for the Development of the Forestry Complex of the Russian Federation until 2030 [8] does not take into account possible changes in wood stocks caused by climate change. In [7], on the basis of modeling data obtained on the sample plots of the Arkhangelsk region (northern taiga), data on the increase in stands growth from 3 to 6 percent for every 100ºC of the sum of effective
temperatures is presented. The calculations of the predicted value of the stock of growing in the subjects of the Russian Federation by 2050–2059, obtained in [3], were adjusted for this dependence. Calculations were made on the lowest point of the scale (growth of stands - 3% for every 100 °C sum of active temperatures) and at the highest point of the scale (growth of stands - 6% for every 100 °C sum of active temperatures). According to the results of the updated calculations, it is expected that the total stock of plantations will be from 120.9 billion m$^3$ to 125.1 billion m$^3$, the annual increase may be from 1,090.5 million m$^3$ per year to 1,212.6 million m$^3$ per year. The greatest increase is expected in the regions of southern taiga and more southern regions (from 17% to 33% of the increase). An increase in the sum of effective temperatures is likely to occur most actively, mostly in sparsely-wooded regions of Russia (Central, Central Black Earth regions, Volgograd region, Rostov region, North Caucasus, Volga region), no significant change is expected for forestry activities in these subjects.

In the regions of northern taiga and middle taiga, the growth may be from 13% to 26% by the middle of the century. It is expected that some species of trees may be replaced by climatypes, especially in the territory of border forest areas. Due to the rather narrow planning horizon - until the middle of the XXI century, the widespread replacement of conifers by deciduous trees should not be expected, it will occur gradually, mainly at the cutting sites. In connection with this, thinning care in the medium and long term needs to pay more attention and use a large proportion of planting material with a tubed nursery stock. In mature and over-mature dark conifer plantations, due to the high acidity of the soil, caused by the needles fall, the replacement with deciduous plantations may occur more slowly, climate change will affect the growth of mortality by reducing the resistance, drying out of tree plantations and the subsequent spread of woodborers. Due to this, coniferous stands are expected to increase the planned volumes of sanitary cuttings.

Due to the complex dynamics of hydrological processes occurring in wetland ecosystems, it is currently difficult to predict how climate change will affect peatlands. Taking into account the data obtained, it is possible to hypothesize a lowering of the groundwater level in the southern regions and the release of some of the carbon from the pools of Western Siberia.

At the same time, various studies show a reduction in permafrost zones by the middle of the century [13]. By the years 2050-2059 warming of average daily air temperature is expected in permafrost regions, incl. in Nenets AO, Yamalo-Nenets AO, Khanty-Mansiysk AO, Chukotka AO. This can lead to waterlogging of these areas and the creation of additional carbon pools. Additional studies are required to assess the impact of climate change on these ecosystems.

As of 01/01/2016, the ratio of the volume of the estimated cutting area to the total timber stock is 0.85%. It can be expected that by 2050, according to rough estimates, the volume of the estimated cutting area will be from 1,027.3 to 1,063.6 million m$^3$, mostly coniferous species. In the case of maintaining the assessment of the availability of forest plantations, produced by FAO as of 01/01/2016 (45%), the volume of economically viable harvesting can reach 478.6 million m$^3$.

Calculations of the increase in stock, made according to the RCP-8.5 outline, show that the annual increase because of climate change and growth in the productivity of plantations will be from 218.1 to 242.5 MtC per year.

In [6], it was concluded that the number of days of fire control in forestry is increasing due to climate change. It is expected that by 2050–2059 on the territory of the Russian Federation, the number of fire danger days will increase by an average of four days. The greatest changes in the indicator are expected in the European-Ural part of the middle and southern taiga, Eastern Siberia, southern taiga, in the Far East in the middle taiga, and in the southeastern part of Western Siberia. In a number of regions, a decrease in the number of days of fire danger is expected: the Leningrad Region, the Novgorod Region, the Pskov Region, the Kaliningrad Region, the Republic of Adygea, the Krasnodar Territory, the Stavropol Territory, and the Krasnoyarsk Territory. The decrease in the number of days of fire danger in the described regions may be due to an increase in the wetting index by the middle of the century, exceeding the average for the subjects of the Russian Federation.
It can be expected that with the change in the number of days of fire danger, the number of forest fires will increase, which may lead to an increase in GHG emissions as a result of the release of combustion products into the atmosphere in the territory of the Russian Federation by the middle of the century. Such estimates are consistent with the conclusions on the contribution of global warming to changes in the statistics of fire-hazardous days obtained in other studies [14]. According to the data presented in the National Report on the inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol for the period of 1990-2016 [12], the average value of greenhouse gas emissions from forest fires is 64.7 tons C per hectare of forest fires. By correlating data on the average value of the area of forest fires and greenhouse gas emissions over the period 1990-2016 with the forecast indicators calculated by the formula 1, it can be determined that the current average level of these indicators corresponds to 217 days of fire hazard III-V of the KPO level for Nesterov when fire area is 2 776 305.8 ha per year, the emissions amount is 179.6 MtC per year. If the number of days of fire danger increases to 221 by the middle of the century, the area of fires may increase to 3,667,540.2 hectares, the volume of emissions may increase to 237.3 MtC per year. The volume of increase in greenhouse gas emissions by the middle of the century could be 57.7 MtC per year. Figure 3 shows the expected carbon balance structure of forests in Russia by 2050–2059.

![Figure 3. The forecast of the carbon balance structure of Russia by 2050–2059.](image-url)
5. Conclusion

By assessing greenhouse gas emission levels for a long-term period of forestry development, it is necessary to take into account the key biotic and abiotic factors that are influenced by climatic changes: the productivity of forest plantations and the fire control in forestry. The productivity of the stand in the taiga is influenced by the level of moisture and the ambient temperature. Taking into account the forecast data, it can be concluded that forest productivity may increase by the middle of the century, which may lead to an increase in forest plantations to 125.1 billion m$^3$. Due to the displacement of the borders of the southern taiga in the North it is expected the replacement of conifers by deciduous, which will increase the volume of phytomass. This will positively affect the increase in carbon pools and increase the potential amount of wood harvesting.

According to the CBM-CFS3 [6] forecast for the full carbon balance of Russian forests by 2050, the minimum estimate for all carbon pools is expected to be 114.6 MtC per year. These data do not take into account the effects of expected climate change. Taking into account the annual increase as a result of growth in plant productivity, (218.1-242.5 MtC per year), an increase in greenhouse gas emissions as a result of wood removal in the implementation of harvesting scenarios (48.2-87.5 MtC per year) and an increase in greenhouse gas emissions from the occurrence and spread of forest fires (57.7 MtC per year), it can be expected that the difference between the increase in carbon sink and carbon loss will be 72.9-136.6 MtC per year, which means maintaining a positive carbon balance of Russian forests in the implementation of all forest management scenarios stipulated by the Strategy for the Development of the Forestry Complex of the Russian Federation until 2030, by mid-century. The overall carbon balance of Russia is expected to be at the level of 187.5-251.2 MtC per year, depending on forest use scenarios and growth in planting productivity, which corresponds to the current level of 150-200 MtC per year.

The calculations made show that the effects of climate change will not be key constraints to the development of forestry, the expected growth in the productivity of plantations exceeds the planned rate of increase in logging volumes. At the same time, due to the increase in temperature, an increase in the number of days of fire danger is expected according to the complex indicator of Nesterov. This can lead to an increase in the number of fires that cause the release of carbon into the atmosphere. The process of replacing conifers with deciduous will lead to an increase in natural loss, which, in conditions of increasing fire danger, may increase the area of forest fires. Lack of moisture in the southern regions of the country can lead to deforestation. An increase in temperature can lead to a decrease in the level of groundwater and the release of carbon from peatlands. All these factors will have an impact on economic activities in forests and will require the implementation of a set of adaptation measures.

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References

[1] Law E A, Thomas S, Meijaard E, Dargusch P J and Wilson K A 2012 A modular framework for management of complexity in international forest-carbon policy Nature Climate Change 2 155-160
[2] Bass S, Dubois O, Moura-Costa M 2000 Rural livelihoods and carbon management International Institute for Environment and Development London 106 p
[3] Smith J, Scherr S J 2002 Forest Carbon and Local Livelihoods: assessment of opportunities and policy recommendation CIFOR Occasional Paper (No. 37) 56 p
[4] Van Vuuren D P, Edmonds J A, Kainuma M, Riahi K, Thomson K, Hibbard K, Hurtt G C, Kram T, Krey V, Lamarque J F, Masui T, Meinshausen M, Jakenovic N, Smith S J, Rose S 2011 The representative concentration pathways: an overview Climatic Change 109(5) 5–31 10.1007 / s10584-011-0148-z
[5] Shkolnik I, Pavlova T, Efimov S and Zhuravlev S 2017 IPC RCP8.5 scenario Climate
Dynamics DOI: 10.1007/s00382-017-3600-6

[6] Torzhkov I O, Kushnir E A, Konstantinov A V, Koroleva T S, Efimov S V, Shkolnik I M 2019 Predicted climate changes and their impact on the forest sector of the Russian economy *Meteorology and Hydrology* 3 40-49

[7] Nakvasina E N, Prozherina N A, Chuprov A V, Belyaev V V 2018 The growth of Scots pine on climatic changes in the latitudinal gradient *News of Higher Educational Institutions. Forest Journal* 5 82-93

[8] Strategy for the development of the forest complex of the Russian Federation until 2030 2018 Approved. Order of the Government of the Russian Federation of September 20 2018 No 1989-p 102p

[9] Zamolodchikov D G, Grabovskiy V I, Kruts V A 2014 The Impact of Forest Use on the Carbon Balance of Russia's Forests: Forecast Analysis Using the CBM-CFS3 Model *Proceedings of the St. Petersburg Forest Research Institute* 1 5–18 ISSN 2079-6080

[10] Sherstyukov B G Sherstyukov AB 2014 Estimates of the fire control in forestry on the territory of Russia with climate warming in the 21st century *Proceedings of VNIIGMI-WDC* Issue 178 Retrieved from: http://meteo.ru/126-trudy-vniigmi/trudy-vniigmi-MtCd-vypusk-178-2014-g / 537-otsenki-opasnosti-lesnykh-pozharov-na-territorii-rossii-pri-poteplenii-klimata-v-xxi-veke

[11] Dumnov A D, Maximov Yu I, Roshchupkina YuV, Aksenova O A 2005 *Forest fires in the Russian Federation Statistical handbook* 229 p

[12] National report on the inventory of anthropogenic emissions from sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol for the years 1990-2016. 2018 Moscow Retrieved from: https://unfccc.int/sites/default/files/resource/rus-2018-nir-14apr18.zip

[13] Klimenko V V, Tereshin A G, Mikushina O V 2008 Changes in climatic parameters and their role in the work of the country's heat supply systems *Journal “News of Heat Supply”* 8 (96)

[14] Settele J, Scholes R, Betts R 2014 Terrestrial and inland water systems *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* Cambridge Cambridge University Press P 271-259