THE ROLE OF FORESTS IN THE CARBON CYCLE: MECHANISMS OF CARBON ABSORPTION AND STORAGE

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Abstract

Forests play a key role in the carbon cycle, acting as major carbon sinks and important carbon stores on Earth. This article examines how forest ecosystems perform photosynthesis, the process by which they capture carbon from the atmosphere and convert it into organic matter. Particular attention is paid to the various mechanisms of carbon assimilation, such as the transformation of carbon into biomass, roots and soil, as well as its long-term storage. One of the main factors influencing the efficiency of carbon absorption is the forest type. For example, tropical forests, due to their high biomass and species diversity, absorb significantly more carbon compared to temperate and boreal forests. The influence of climatic conditions, such as temperature and rainfall, on the process of photosynthesis and tree growth is also considered. Forest age also plays an important role: young forests accumulate carbon faster, while old forests can reach a state where carbon accumulation slows down. The article also highlights the importance of preserving and restoring forest ecosystems as a strategic approach to combating climate change. Increasing forest area and implementing sustainable forest management practices can significantly increase their capacity to absorb carbon, as well as improve other ecosystem services such as maintaining biodiversity and protecting soil from erosion. Importantly, forest destruction caused by logging and land tenure change releases significant amounts of carbon into the atmosphere, exacerbating the problem of climate change.

Keywords: forests, carbon cycle, carbon sequestration, carbon storage, climate change, ecosystem services, photosynthesis, sustainable forest management, forest restoration

I. Introduction

Despite the growing trend towards fragmentation of the global economy, the loss of influence of various international organizations and the weakening of previously concluded agreements, the idea of preventing catastrophic climate change, first enshrined in the UN Framework Convention on Climate Change (UNFCCC) in 1992, continues to be relevant and receives support from all countries of the world. Russia, although reducing its participation in various interstate initiatives in recent years, nevertheless emphasizes its commitment to decarbonization of the economy. The Low Carbon Development Strategy (LCDS) [1], adopted in October 2021, sets the goal of achieving carbon neutrality of the national economy by 2060. In accordance with this strategy, the transition to carbon neutrality is planned to begin only after 2030 (Fig. 1). An important role in this process is given not to measures in the energy sector, which might be expected, but to a more than twofold increase in carbon absorption by the country's forests in the area of land use, land-use change and forestry (LULUCF). This strategy, according to a number of forestry experts [2, 3], is based on rather unreliable foundations and is therefore considered risky.

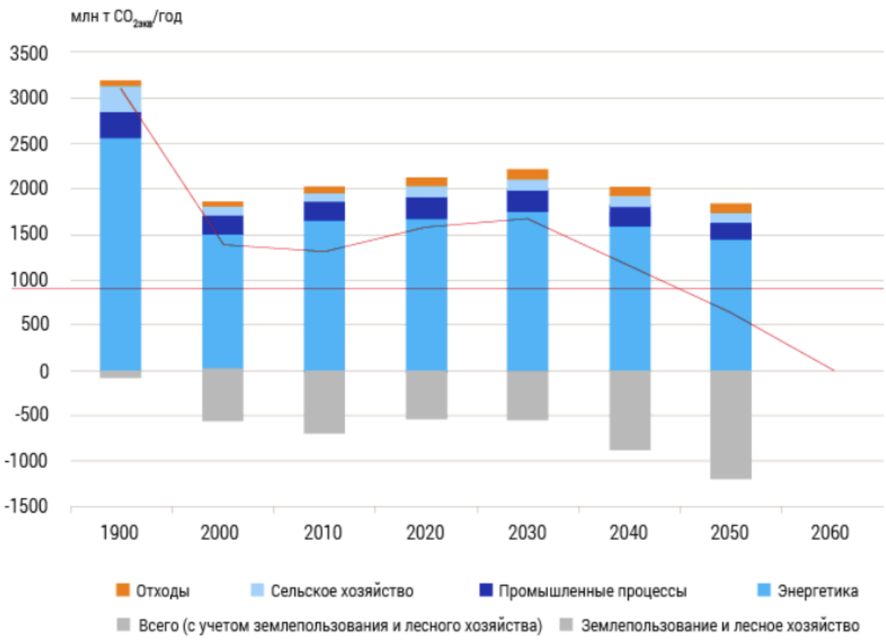

Figure 1: *Target scenario of the Low Carbon Development Strategy*

II. Methods

Low Carbon Development Strategy (LCDS) and its presentation at the UNFCCC Conference of the Parties in Glasgow in 2021 generated a great deal of interest and a number of publications devoted to various aspects of decarbonization of the Russian economy [4–11]. This work aims to assess the feasibility of achieving this goal, taking into account global historical experience, and to identify possible ways to solve this problem.

Over the past thirty years, two main periods have been distinguished in the dynamics of greenhouse gas (GHG) emissions in Russia: a sharp decline in the 1990s and a gradual increase in 2000–2020 (Fig. 1). The minimum net emission (taking into account the absorption of carbon dioxide by biota) was recorded in 2010, which is associated with an increase in the absorption capacity of forests due to a reduction in the volume of timber harvesting and the overgrowing of abandoned agricultural lands.

While the drop in emissions in 1990–2000 affected virtually all sectors of the national economy and affected emissions of all greenhouse gases (including carbon dioxide, methane, nitrous oxide, chlorofluorocarbons , and others), the subsequent partial recovery in emission volumes occurred primarily in the energy sector and, to a lesser extent, in industrial processes, where carbon dioxide emissions also increased (Fig. 1). A significant risk to Russia's long-term economic interests is the misconception that increasing the role of forests and properly accounting for this role can solve the practical tasks of the Paris Agreement and the Low Carbon Development Strategy (LCDS) to reduce greenhouse gas emissions without systematic actions to green the economy as a whole, especially in the energy sector. The temptation to rely on such a solution to the problem is great and is due to obvious geographic factors. According to the World Bank, about 20% of the world's forest cover is in Russia. These forests have the potential to become one of the key environmental donors in terms of greenhouse gas absorption and play a leading role in the formation of the carbon balance. Therefore, from the point of view of carbon regulation at the national level within the framework of the Paris Agreement and the goals outlined in the LULUCF [1], it is extremely important to correctly assess the net sink of the land-use change and forestry (LULUCF) sector in Russia and its dynamics in the coming decades. It should be emphasized that estimates of the current carbon balance in Russian forests and its dynamics in the coming decades vary significantly [2–3, 8-11]. Differences in estimates of even the current net flow, conducted by various institutions, can reach fourfold. There are diametrically opposed opinions on further changes in the net sink: from its dramatic reduction by more than five times [3] to a twofold increase by the middle of the century, which is directly reflected in the LULUCF concept [1]. For example, recent research by the World Resources Institute shows that between 2001 and 2019, net carbon sinks in Russia's forests averaged 1.79 billion tonnes of CO_2- eq per year, equivalent to 24% of the world's total forest sinks. These results are also consistent with Boston estimates. Consulting Group (BCG) [15], which record annual absorption by Russian forests in the range of 1.8 to 2.2 billion tons of CO_2- eq ., as well as data from Global Forest Watch , indicating similar removal values of 1.74 billion tonnes of CO_2- eq over the period 2001–2021.

From the point of view of Russia's official reporting under the United Nations Framework Convention on Climate Change (UNFCCC), according to the National Inventory Report of Anthropogenic Emissions by Sources and Removals by Sinks of GHGs [12], in 2021 the greenhouse gas balance in the land-use change and forestry (LULUCF) sector updated the minimum since 2000 and amounted to 484.8 million tons of CO_2-eq . per year, which is equivalent to a 13% decrease in net sink compared to previous estimates submitted to the UNFCCC. It is necessary to note not just an unprecedented decrease in absorption for lands classified as hayfields and pastures, for which the average absorption over a five-year period (2016–2020) was 44.5 million tons of CO_2- eq . per year, but a complete absence of runoff for this land category in 2021 and a total emission of 3.8 million tons of CO_2- eq . For forest lands, there is also a decrease in net runoff, but less significant on a category scale - by 3.8% compared to 2020, namely by 23.5 million tonnes of CO_2- eq , which may be associated with record forest fires in 2021 (Figure 2).

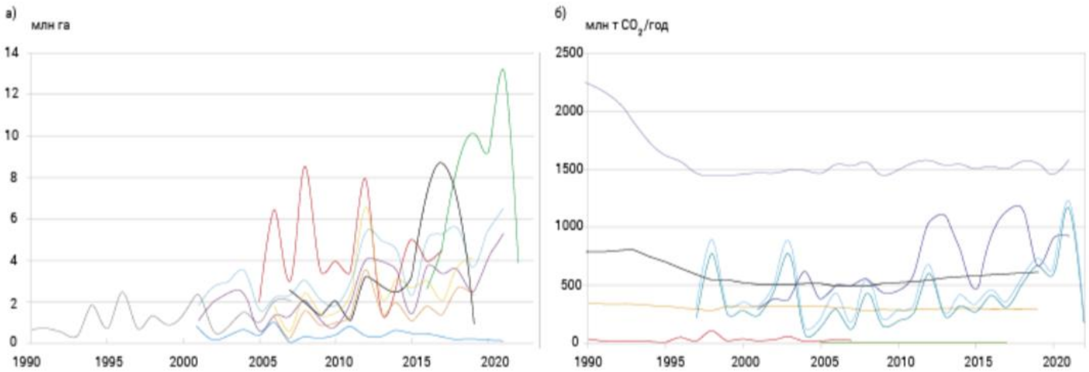

Figure 2: *Forest areas burned and forest loss from fires (a) and carbon dioxide emissions from forest loss compared to emissions from fuel combustion (b) in Russia*

The traditional methodology for assessing national anthropogenic greenhouse gas removals in the land-use change and forestry (LULUCF) sector is the guidelines for national greenhouse gas inventories developed by the Intergovernmental Panel on Climate Change (IPCC) [2] and their supplements [3]. The list of carbon pools and land-use categories remains classical and, without undergoing significant changes, is used by all researchers to assess the carbon budget.

Methods for estimating both removals and emissions of CO_2 equivalent are based on two main approaches. The first, the biomass gain and loss method, involves determining the annual change in carbon stock as the difference between annual carbon gains and losses in tonnes, and is a function of carbon changes and losses. The second approach, the stock difference method, is considered preferable due to its high accuracy and reliability, as it is characterized by the difference in carbon stocks in reservoirs at two specific points in time. However, regardless of the approach chosen, one of the main difficulties remains the identification of the age, stock, and species composition of forest areas, which are used as the main sources of data for the calculations.

In Russia, the official methodology approved by the Ministry of Natural Resources is the methodology of regional assessment of forest carbon budget (ROBUL), developed by the Institute of Global Climate and Ecology (IGCE) named after Academician Yu. A. Izrael and the Center for Forest Ecology and Productivity (CEPL) of the Russian Academy of Sciences (RAS) [5]. This methodology was verified within the framework of the UNFCCC and is intended to provide a unified approach to assessing the carbon budget in Russian forests.

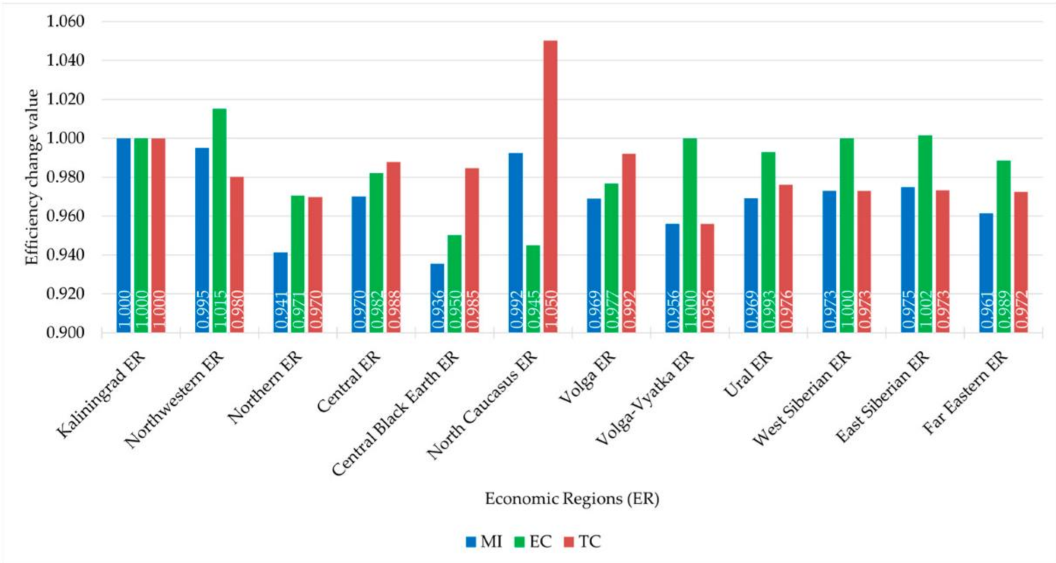

Figure 3: *Average total factor productivity and efficiency changes of forest carbon sinks among economic regions in Russia from 2009 to 2021.*

Further decomposition of the technical efficiency change values is presented in Fig. 3. As mentioned before, three regions, namely Kaliningrad, Volga-Vyatka, and West Siberian ERs, did not perform any efficiency improvements, therefore their PTE and SE values remained unchanged. Along with them, six DMUs (namely Central, Central Black Earth, North Caucasus, Ural, and Far Eastern ERs) kept their management regimes (PTEs) unmodified. During the study period, related improvements occurred in Northwestern ER (1.4%) and East Siberian ER (0.1%), while Northern and Volga ERs deteriorated by 3.5% and 2.3%, respectively. Therefore, these changes made a significant contribution to their performance. As stated before, deterioration in terms of scale efficiency is the main factor hindering the productivity of forest carbon sinks in Russia. In particular, the related value sufficiently decreased in the predominantly agricultural regions of Central Black Earth and North Caucasus ERs, accounting for 5% and 5.5%, respectively. Meanwhile, Central, Volga, Ural, and Far Eastern ERs decreased only by 1.8%, 0.1%, 0.7%, and 1.1%, respectively. Noteworthy, the scale efficiency increment in forest carbon sinks occurred in the Russian North, namely in Northwestern (0.2%) and Northern (0.5%) ERs. As stated in the report [7] by the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), high warming rates occurred in these territories, presumably contributing to local forests absorbing more carbon.

III. Results

Our estimates show a large, long-term persistent sink of 3.56 ± 0.37 Pg C yr−1 in global forests since at least 1990, with a statistically insignificant change, based on Monte Carlo simulations and Cohen's d (Supplementary Fig. 1). Although stable overall, the contribution to this carbon sink of different forest biomes has fluctuated greatly over time. In the tropics there has been a shift from equal contributions of intact and regrowth tropical forests in the 1990s to 65% of the sink being in regrowth forests in the 2010s, as the intact sink declined and the regrowth sink increased (Table 1). Boreal and temperate forests contributed similar carbon sinks in the 1990s, but by the 2010s the boreal sink had decreased to less than half of the temperate sink (Table 1). Carbon stock densities (Mg C ha−1) in all forest biomes in all climate zones steadily increased (Extended Data Fig. 2c), indicating that forest ecosystems across the planet continuously sequestered carbon, implying that a universal growth factor, or several factors, was enhancing forest sinks on continental scales. A suite of multidisciplinary evidence indicates that the global carbon-sink persistence and carbon-density increases were in part the result of CO2 fertilization contributing to substantially increased photosynthesis17,18, as well as to longer growing seasons in temperate and boreal regions26. These factors may have outweighed the negative effects on forest carbon from global heating, changing rainfall patterns and changes in the frequency and severity of natural disturbances in the remaining forests.

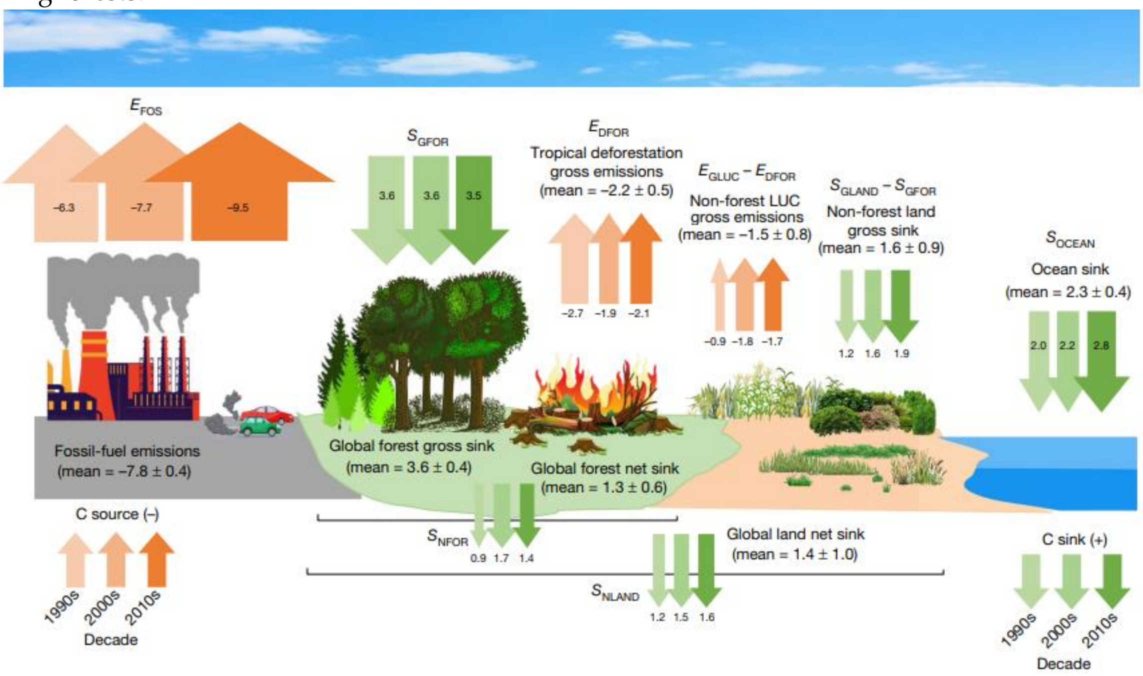

Figure 3: *Integration of inventory-based global forest carbon fluxes with the GCB*

The carbon pool of the world's forests is exposed to risks from deforestation, degradation, and disturbance caused or exacerbated by climate change. In intact tropical forests, the main threats are ongoing deforestation and degradation, which are the main drivers of reduced carbon sequestration (Extended Data, Figure 1). Increasing frequency and severity of droughts have also killed millions of trees, weakening the carbon pool in the Amazon. Given that the combined pool in intact and recovering forests remains stable, the net carbon sequestration for tropical forests as a whole is largely determined by the level of emissions from deforestation. Reducing deforestation and degradation is the only way to keep the carbon stored in forests from escaping into the atmosphere. Protecting tropical forests also helps to maintain their biodiversity and their capacity to sequester carbon into the future.

Boreal forests have been significantly impacted by climate change, including greater temperature increases and variations than other regions. Climate change has disrupted carbon cycling in vegetation and soils, and has increased the impacts of wildfires, pest outbreaks, and droughts. The high levels of carbon storage and sequestration in boreal forest necromass threaten to increase decomposition rates and wildfires during drought conditions. These impacts have made Canadian forests a carbon source, while forests in Asian Russia have lost 42% of their carbon sequestration capacity over three decades, particularly in the late 2010s. Future threats to boreal forest carbon dynamics also include northward shifts in bioclimatic zones, leading to permafrost thawing and megafires such as those that occurred in 2020–2022, as well as increased risks of major pest outbreaks and increased legal and illegal logging, which in turn releases methane and CO_2 .

Temperate forests include the most intensively managed forest ecosystems on Earth. Increased carbon sequestration in these forests is mainly due to past tree planting in China. Temperate forests regenerated on abandoned agricultural land or heavily logged forests in the first half of the 20th century are now approaching an age where their growth rates begin to decline, although growth trajectories and successional dynamics vary within the temperate forest biome. Climate change has increased the frequency and intensity of natural disturbances, which in turn has caused more severe bark beetle outbreaks after droughts in some European forests. In addition, increased deforestation in the temperate zone over the past three decades (+17%) has reduced carbon stocks.

IV. Discussion

To assess the possibilities of achieving carbon neutrality, a comparative analysis of the processes taking place in the economy, especially in the energy sector, in a number of countries was conducted. Both the leaders of decarbonization (the European Union, Japan, the United States and Canada) and the largest developing economies that are just beginning their path to the declared carbon neutrality (China, India, Turkey) are included.

In the energy sector, for the leading countries representing industrially developed economies, there is a transition to stabilization of specific (per capita) energy consumption with its moderate reduction. While in developing economies, including Russia, this indicator continues to grow.

When analyzing the carbon intensity of energy consumption, no significant division is observed. In most countries (EU, USA, Japan, China, Turkey) the trend towards decreasing specific emissions in the energy sector has been maintained over the past 50 years (with the exception of a three-year period in Japan, when there was a mass closure of nuclear power plants after the Fukushima accident in 2011). In Canada, this indicator stabilized back in 1985 at an unprecedentedly low level due to the widespread use of hydro and nuclear energy. In Russia, this indicator has stagnated since 2008, remaining slightly below the world average, while India's energy sector has demonstrated surprising constancy over the entire 50-year period due to the predominance of coal in the national energy balance.

The events of the last year have radically changed all previously existing forecasts of economic development, both for Russia and for many other countries. In this regard, for our study, which sets the task of risky extrapolation of the intensity of policy to curb greenhouse gas emissions for several decades ahead, the method of historical extrapolation was chosen instead of the traditional approach based on detailed assumptions about economic development. We are confident that historical extrapolation can yield useful results, which is confirmed by our experience in creating long-term forecasts for the development of global energy. For example, forecasts compiled in 1990 showed a coincidence with actual data on energy consumption in the world within 2% over a horizon of more than 30 years. However, taking into account the unusually high dependence of the final result on political decisions, we decided to consider two extreme scenarios of Russia's movement towards climate neutrality: an optimistic one and a real one, which takes into account, among other things, current turbulent events. The UN median scenario was chosen as the demographic scenario in both options, which assumes a gradual decrease in the country's population to 128 million by 2060.

The optimistic scenario is based on the assumption that ideas about the fight to preserve the climate will gain much greater influence in Russian society, comparable to that observed in developed countries over the past three decades. In this case, Russia will be able to count on decarbonization rates that correspond to the best world standards (see Table 2). In general, the parameters of the optimistic decarbonization scenario are as follows:

- The rate of reduction of specific (per capita) anthropogenic greenhouse gas emissions is 1% per year, which corresponds to the average value for developed countries in the period from 1990 to 2020.

- Forest management indicators follow the Strategy-2030 (2021) and assume full restoration of forests after all clear-cutting; the dynamics of carbon absorption by forests corresponds to high national estimates, which, it should be noted, significantly diverge from international recommendations.

- Additional carbon fixation by forests is taken into account, taking into account changes in climatic factors (temperature and precipitation), as well as the fertilization effect resulting from an increase in the concentration of carbon dioxide in the atmosphere.

- A 50% reduction in the area of forest fires is being implemented (in accordance with the Decree of the President of the Russian Federation) by 2030, with this indicator being maintained in the future.

The real decarbonization scenario takes into account the difficulties associated with the radical restructuring of all sectors of the economy - from energy to forestry - and is characterized by the following parameters:

- The rate of reduction of specific (per capita) anthropogenic greenhouse gas emissions corresponds to the moderate indicators achieved in Japan and Canada in the period from 1990 to 2020, and amounts to 0.5% per year, which is significantly better than current Russian indicators.

- Forest management indicators follow current international recommendations and are based on the results of official forest inventories and the Forest Strategy 2030, taking into account the real prospects for the development of the forest sector and the dynamics of carbon absorption by forest biota , according to which the net carbon sink shows a slight increase. In this scenario, ageing forests lose their bioproductivity , but technically and economically feasible forest climate projects are implemented in forestry , while the fight against forest fires achieves limited success.

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