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Carbon stocks in the forests of the Ural Region

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Abstract

This paper examines carbon stocks in the forests of the Ural region forest fund. Carbon deposition in forest biomass, the average, average annual and annual carbon absorption were assessed by age groups and dominant species. The average annual rates of forest destruction were estimated depending on the territory of forest fires and burnt areas. Carbon losses in the biomass pool after continuous logging were estimated according to the methodology "On approving guidance to calculate greenhouse gas emissions" developed by the Ministry of Natural Resources of the Russian Federation. Carbon storage indicators were calculated from the groundwood of coniferous, hard-leaved and soft-leaved forests for all age groups. Changes in carbon stocks are shown for the period 2007–2018. The forests of the study area, the Republic of Bashkortostan, were found to sink carbon in 3,618.9 thousand tons/year. *Pinus sylvestris* L. forests accumulate the largest amount of carbon, 58,384.3 thousand tons, among coniferous forests. The difference between carbon absorption and its budget was 3,124.4 thousand tons/year. Soft-leaved stands that dominate in the republic accumulate the largest total carbon stock being 195,900.2 thousand tons. However, their average level of carbon stock is lower than that of coniferous and hard-leaved forests. Maintaining the level of carbon dioxide uptake is a strategic task of the republic's forestry sector, with compensatory reforestation being one solution.

Keywords: absorption; carbon, coniferous forests, deciduous forests, storage, wood harvesting

Introduction

Forest stands perform many functions, including mitigating climate change, reducing greenhouse gas emissions, maintaining sustainability, and increasing ecosystem biodiversity (Brandt et al. 2013, Kurz et al. 2013, Waring et al. 2020, Fradette et al. 2021). Carbon storage is another important ecosystem service, as trees and other forest vegetation act as CO_2 sinks (Hosonuma et al. 2012, Ismail et al. 2018).

To ratify the Paris Agreement of 2019, Russia must implement international commitments on state regulation of industrial emissions, closely related to developing a method to estimate forest carbon stocks (Filipchuk et al. 2017, Farooqi et al. 2021). Many authors believe that forests play a dominant role in carbon sink. The multi-faceted scholarly papers present the carbon balance assessment and the calculation of the carbon budget in forests at the regional and international levels (Zamolodchikov et al. 2011, Filipchuk et al. 2017, Pache et al. 2021). Thus, Canadian researchers started to consider carbon stocks in their forests in the 90s of the XX century. As a result, they have developed an open software package to assess the carbon storage and balance for different forest zones of Canada, equipped with a detailed interface for users (Colombo et al. 2005, Kull et al. 2006, Liu et al. 2011, Stinson et al. 2011). The Russian Forestry Service has tested the method of predictive assessment of the forest use impact on the carbon budget of Canada. RosHydroMet (Federal Service for Hydrometeorology and Environmental Monitoring) uses this method to compile an inventory of greenhouse gas sources and calculates the carbon balance expenditure resulting from logging and forest fires (Zamolodchikov et al. 2011, Zamolodchikov et al. 2014).

A height growth and development period of coniferous and deciduous species, long biological cycles of forest substances lead to large amounts of carbon stocks deposited by all forest components. Due to the long-term accumulation of carbon in forest ecosystems, a high biosphere effect is achieved, associated with the absorption of greenhouse gases and climate change (Malysheva et al. 2017).

Thus, forests stabilize the composition of atmospheric air by replenishing it with oxygen and neutralize man-made emissions by absorbing carbon dioxide, methane, and other substances. Forests in Russia annually uptake 959 million tons of carbon dioxide (Isaev 1995). Forests ensure the quality of the natural environment at the global, national, or regional and local levels. Forest ecosystems are essential for varied ecological functions: they reduce contaminations of the air, soil and water bodies, reduce the greenhouse effect, etc., including those taking place in urbanized areas (Kasimov and Kasimov 2015).

Enhanced forest carbon sequestration and adaptation to climate change have been key issues of scientific and applied research; however, the adaptive potential of forests in the regional aspect has not been sufficiently studied (Malysheva et al. 2017).

The paper aimed to assess carbon stock and its annual absorption by the biomass of coniferous and deciduous forests.

Materials and methods

Site description

The study was conducted in the forests of different natural zones of the Republic of Bashkortostan, namely the South Ural forest-steppe region, being a part of the forest-steppe region of the European part of Russia and the coniferous-broad-leaved region of the European part of Russia, using data from the State Forest Fund Accounting for 2007 and the State Forest Register for 2018. Most of the Ural's climate is continental with cold winters and relatively hot summers, sharp daily and annual temperature changes. The study area is rolling and includes the Ufa plateau, the Bugulma-Belebey Upland, the Prybylski Undulating plain, the Yuryuzan-Aisk plain and the northern spurs of the Obshchyi Syrt in the Northern Mugodzhars. The forest fund of the republic is dominated by soft-leaved stands (3,558,954 ha) with prevailing *Betula pendula* Roth (1,379,837 ha), followed by coniferous species like *Pinus sylvestris* L., *Picea abies* (L.) H. Karst., *Larix sibirica* Ledeb., *Abies sibirica* Ledeb. (1,145,028 ha) and hard-leaved species like *Quercus robur* L., *Acer platanoides* L., *Ulmus glabra* Huds. (458,770 ha) (Table 1) (Head of the Republic of Bashkortostan 2018, Ministry of Forestry of the Republic of Bashkortostan 2018, 2020).

Methods for estimation of carbon sequestration

Carbon uptake, loss and budget in coniferous and deciduous forests were calculated according to the methodology of the Ministry of Natural Resources and Ecology of the Russian Federation (2017). Calculations were based on the data represented in the State Forest Register).

Carbon stock in the forest biomass by age groups and dominant species was calculated by the formula:

$$CP_{ij} = V_{ij} \cdot KP_{ij} \quad (1)$$

where:
CP_{ij} is the carbon stock in the biomass of the age group *i* of the dominant species *j*, tons;
V_{ij} is the stock of stem wood of stands of the age group *i* of the dominant species *j*, m^3/ha;
KP_{ij} is the conversion rate for calculating the carbon stock in the forest biomass of the age group *I* of the dominant species *j*, t/m^3 (Table 2; Ministry of Natural Resources and Ecology of the Russian Federation 2017).

Depending on the age groups of plantings (young (1–20 – deciduous, 1–40 – coniferous), middle-aged (21–30 – deciduous, 41–60 – coniferous), ripening (31–50 – deciduous, 61–100 – coniferous), mature (51–70 – deciduous, 101–120 – coniferous) and overmature (above 71 – deciduous, above 121 – coniferous), the conversion rates used in determining the carbon stock are adopted under the methodological guidelines for quantifying

Table 1. The forest area by age group in the context of farms (coniferous, hard-leaved, soft-leaved), thous. hectares

Species	Age group					
	Young stands		Middle-aged stands	Ripening stands	Mature and overmature stands	Subtotal
	1st class	2nd class				
Coniferous						
Scots pine	162.8	186.4	135.6	93.6	209.7	788.1
Norway spruce	128.1	58.6	20.8	20.9	39.9	268.3
Siberian larch	4.0	5.0	10.2	10.0	13.5	42.7
Siberian fir	6.2	6.6	8.3	6.8	18.0	45.9
Siberian pine	0.1	0.07	0.01			0.18
Total	301.2	256.7	174.9	131.3	281.1	1145.2
Hard-leaved						
Pedunculate oak, seedling	0.6	1.1	2.1	1.4	3.7	8.9
Pedunculate oak, sprout	2.6	3.0	76.9	45.6	121.6	249.7
Others (Elm, Maple, Ash)	3.6	8.8	38.1	13.7	135.8	200.0
Total	6.8	12.9	117.1	60.7	261.1	458.6
Soft-leaved						
Silver birch	55.1	33.5	321.7	217.0	752.5	1379.8
Eurasian aspen, Poplar	93.7	97.9	102.2	92.4	399.9	786.1
Others (Alder, Linden, Willow)	32.2	47.2	380.8	231.5	701.1	1392.8
Total	181.0	178.6	804.7	540.9	1853.5	3558.7

Table 2. Conversion rates (according to the Ministry of Natural Resources and Ecology of the Russian Federation, 2017)

Dominant species	Age group			
	Young stands	Middle-aged stands	Ripening stands	Mature and over-mature stands
Scots pine	0.435	0.352	0.329	0.356
Norway spruce	0.614	0.369	0.351	0.364
Siberian fir	0.420	0.308	0.283	0.270
Siberian larch	0.392	0.371	0.398	0.398
Siberian pine	0.392	0.341	0.319	0.450
High-stemmed oak	0.616	0.491	0.418	0.478
Low-stemmed oak	0.796	0.541	0.563	0.637
Other hard-leaved trees	0.624	0.477	0.388	0.436
Silver birch	0.437	0.396	0.367	0.367
Eurasian aspen, poplar	0.356	0.363	0.335	0.365
Other soft-leaved trees	0.381	0.336	0.334	0.337

the volume of greenhouse gas uptake (Ministry of Natural Resources and Ecology of the Russian Federation 2017).

The average, average annual, and annual carbon uptake by the biomass pool were calculated using formulas 2–4:

$$MCP_{ij} = \frac{CP_{ij}}{S_{ij}} \qquad (2)$$

where

MCP_{ij} is the average carbon stock of the biomass of the age group i of the dominant species j, t/ha;

CP_{ij} is the carbon stock of the biomass of the age group i of the dominant species j, t;

S_{ij} is the area of plantings of the age group I of the dominant species j, ha.

$$MAbP_{ij} = \frac{MCP_{ij} - MCP_i - 1j}{TI_i - 1j + TI_{ij}} + \frac{MCP_i + 1j - MCP_{ij}}{TI_{ij} + TI_i + j} \qquad (3)$$

where:

$MAbP_{ij}$ is the average annual carbon uptake by the biomass pool of the age group i of the dominant species j, t/ha/year;

MCP_{i-1j} is the average biomass carbon stock of the age group $i - 1$ (preceding the age group i) of the dominant species j, tons/ha;

TI_{ij} is the time interval of the age group i of the dominant species j, years (Table 4);

TI_{i-1j} is the time interval of age group $i - 1$ of the dominant species j, years (Table 3);

MCP_{i+1j} is the average biomass carbon stock of the age group $i + 1$ (following the age group i) of the dominant species j, t/ha;

TI_{i+j} is the time interval of the age group $i + 1$ of the dominant species j, years (Table 3);

$$AbP_{ij} = S_{ij} \cdot MAbP_{ij} \qquad (4)$$

where:

AbP_{ij} is the annual carbon absorption by the biomass pool of the age group i of the dominant species j, t/year.

The average annual rates of forest destructions are estimated by the formulas 5, 6:

$$ASF = \frac{SB}{TRB} \qquad (5)$$

where:

ASF is the annual area of destructive forest fires, ha/year;

SB is the burnt areas, ha;

TRB is the time of the burnt area regeneration, years (Table 4).

$$ASH = \frac{SC}{TRC} \qquad (6)$$

where:

ASH refers to the annual area of continuous logging, ha/year;

SC is the logging area, ha;

TRC is the time of regeneration of cutover stands, years. The regeneration time of cutover stands and burnt areas on the territory of the Republic of Bashkortostan is taken to be 5 and 10 years.

Estimation of carbon losses in the biomass pool during continuous logging:

$$LsPH = \frac{ASH\ CPm}{Sm} \qquad (7)$$

where:

$LsPH$ is the annual carbon loss by the biomass pool of forested land during continuous logging, t/year;

ASH is the annual area of continuous logging, ha/year;

CPm is the total carbon stock of the biomass of mature forests, t;

Sm is the total area of mature forests, ha.

Table 3. Time intervals of the planting age groups by dominant species

Dominant species	Time interval of age groups, years					
	Young stands		Middle-aged stands	Ripening stands	Mature stands	Overmature stands
	I *	II *				
Scots pine, Norway spruce, Siberian fir, high-stemmed oak	20	20	20	20	40	40
Larch	20	20	40	20	40	40
Siberian pine	40	40	120	40	80	80
Low-stemmed oak	10	10	30	10	20	20
Other hard-leaved trees	20	20	20	20	40	40
Silver birch	10	10	30	10	20	20
Aspen, other soft-leaved trees	10	10	20	10	20	20
Other	5	5	10	5	10	10
Total	181.0	178.6	804.7	540.9	1853.5	3558.7

* Note: I – young stand of the first age group, II – young stand of the second age group.

Table 4. Total and average carbon stock by wood species and age groups, thous. tons/ha

Species		Age group				
		Young stands	Middle-aged stands	Ripening stands	Old growth and overmature stands	Total
Coniferous	Scots pine	15675 / 44.9	12405.7 / 91.5	10759.8 / 115.0	19544.0 / 93.2	58384.3 / 86.1
	Norway spruce	4377 / 23.5	1537.9 / 73.8	1578.2 / 75.5	3447.9 / 86.5	10941.0 / 64.8
	Fir	237.1 / 26.4	560.7 / 54.9	629.6 / 63.0	740.2 / 54.8	2167.6 / 49.8
	Larch	447.2 / 35.1	726.6 / 87.9	615.3 / 90.8	1254.3 / 69.6	3043.4 / 70.8
	Siberian pine	8.7 / 46.6	0.1 / 13.6	-	-	8.8 / 30.1
	Subtotal	20744.8 / 35.3	15231.0 / 64.3	13582.9 / 86.0	24986.4 / 76.0	74545.1 / 65.4
Hard-leaved	Oak seedling	66.1 / 37.1	147.9 / 70.4	79.4 / 55.7	213.6 / 58.5	507.0 / 55.4
	Oak sprout	116.1 / 20.8	4521.7 / 58.8	3355.9 / 73.6	10059.4 / 82.7	18053.1 / 59.0
	Elm, Maple, Ash	388.1 / 31.3	1898.6 / 49.8	713.6 / 52.1	7637.8 / 56.2	10638.1 / 47.3
	Subtotal	570.3 / 29.7	6568.2 / 59.7	4149.0 / 60.5	17910.7 / 65.8	29198.2 / 53.9
Soft-leaved	Birch	883.6 / 10.0	17401.9 / 54.1	13041.2 / 60.1	45010.5 / 59.8	76337.2 / 46.0
	Aspen, Poplar	2654.3 / 13.9	4237.4 / 41.5	5028.4 / 54.4	29411.5 / 73.5	41331.5 / 45.8
	Alder, Linden, Willow	1143.7 / 13.5	18238.1 / 47.9	12182.9 / 52.6	46666.8 / 66.6	78231.5 / 45.2
	Subtotal	4681.7 / 12.5	39877.4 / 47.8	30252.4 / 55.7	121088.8 / 66.6	195900.2 / 45.7

Forest fires burn forest lands regardless of age. Accordingly, the loss of the biomass pool in fires was estimated by the average indicators for all forests:

$$LsPF = \frac{ASF\ CPa}{Sa} \quad (8)$$

where:
LsPF stands for the annual carbon loss by the biomass pool of forested land during fires, t/year;
ASF is the annual area of destructive forest fires, ha/year;
CPa is the total biomass carbon stock on forested land, t;
Sa is the total area of forested land, ha.

Statistical analysis

The statistical processing is performed using a STATISTICA 6.0 software package (StatSoft 2001). The reliability of potential correlations was evaluated according to the Student's *t*-test ($t \leq 0.05$).

Results

Forest biomass plays a crucial role in the global carbon cycle (Vashum and Jayakumar 2012), and as a CO_2 sink, forests are an economic treasure worth billions of dollars, currently absorbing more than 30% of the world's total carbon dioxide emissions annually (Jallat et al. 2021).

It was found that the carbon sequestration indicators calculated from the groundwood of coniferous, hard-leaved and soft-leaved forests for all age groups differ significantly depending on the species, age composition and productivity of the studied forests. The forested area of the Republic of Bashkortostan is 5,186.5 thousand hectares with a reserve of carbon in the bound state being 91.9 million tons, with accumulated phytomass in the amount of 597.1 million tons. The deciduous stands have the highest carbon absorption intensity, namely 4,930 thousand tons/year by soft-leaved stands; 1,299 thousand tons/year by the coniferous stands ($t_{\text{estimated young and medium-aged stands}} = 4.607$, $t_{\text{estimated young and ripening stands}} = 9.762$, $t_{\text{estimated young, mature and overmature stands}} = 0.849$; $t_{0.05\ \text{tabular}} = 2.086$; $t_{\text{estimated coniferous and soft-leaved stands}} = -1.319$, $t_{\text{estimated coniferous and hard-leaved}} = -0.441$, $t_{\text{estimated hard-leaved and soft-leaved}} = -0.858$; $t_{0.05\ \text{tabular}} = 2.447$). Analysis of plants' average annual carbon absorption by age groups showed that young coniferous trees had the best indicators (Table 4).

The biological and ecological characteristics of wood species and their wood productivity directly impact carbon sequestration. Common spruce annually absorbs 4.6–6.5 t/ha of carbon, releasing 3.5–5.0 t/ha of oxygen (Filipchuk et al. 2017). When these indicators are taken as a standard (100%), the oxygen release and carbon dioxide absorption by Siberian larch are equated to 120%, Scots pine to 160%, small-leaved linden to 250%, common oak to 450%, and balsamic poplar to 700%. According to Filipchuk et al. (2017), Russian forests accumulate 34 billion tons of carbon per year, with coniferous forests accounting for more than 25 billion tons.

There are not many studies around the world concerning carbon stock estimations in pine and juniper forests. In the pinyon-juniper woodlands of the western Colorado Plateau, the average aboveground woody carbon is estimated at 5.2 ± 2.0 Mg C/ha (Huang et al. 2009). Ismail et al. (2018) studied the carbon stock of *Juniperus communis* using Jenkin's allometric equation (Jallat et al. 2021) and estimated the amount of carbon at 1.96 t/ha. The current study found that common pine has the highest total volume of carbon sequestration among coniferous species in the republic, being 27.4%, among deciduous species, a significant amount is contributed by linden (18.3%), birch (17.3%) and aspen stands (15.9%).

Forest stands of the republic sequester carbon in the amount of 3,618.9 thousand tons/year, including aboveground – 2,763 thousand tons/year, deadwood – 468, forest litter – 87.9, soil – 300.2 thousand tons/year. Some authors believe that the impact of forest fires on carbon stocks has been poorly studied at the scale of forest ecosystems, including the effects depending on the forest fire limitation statute, that is, the regeneration time for burnt areas. During the first year after the fire, the total net carbon was 347 g/m^2. The relatively rapid restoration of the ecosystem function was mainly due to the undergrowth and self-seeding of pine (Oliveira et al. 2021). This research shows that carbon losses due to forest fires, logging, insect damage, and infections by harmful organisms amounted to 755.2 thousand tons/year. Brazilian scientists denote that deadwood (fall-off) plays an important ecological function, including carbon accumulation in forest ecosystems. Despite close attention to the role of forests in the global carbon cycle, there is no comparable data on the carbon stock in forest drain for different regions. The authors analyze the terminology and sampling methods related to the quantitative assessment of the carbon stock in forest necromass (Huang et al. 2009, Filipchuk et al. 2017, Egoshin et al. 2018, Maas et al. 2020).

The carbon budget, the difference between absorption and loss, equals 3,124.4 thousand tons/year. The difference between the stock of the sequestered carbon for the period from 2007 to 2018 does not contradict the null hypothesis, where $t_{substr.} < t_{table}$, $p > 0.05$, $P_t > 95\%$. The volume of wood harvesting affects the amount of carbon absorbed by forests (Zamolodchikov et al. 2011), confirmed by this study. An increase in the proportion of overmature soft-leaved forests has led to a decrease in carbon sequestration since 2007. In 2007–2018, larger areas of stands infested with insects and infected by harmful organisms and an increase in the volume of forest harvesting resulted in carbon losses from 537.5 to 755.2 thousand tons (Figure 1).

Among coniferous trees, Scots pine stands of all ages accumulate the largest volume of carbon at 58,384.3 thousand tons, then forests of Norway spruce follow with 10,941.0 thousand tons.

The differences in the average volume of carbon stock in coniferous and deciduous stands by age groups are significant ($t_{substr.} < t_{table}$, $p > 0.05$, $P_t > 95\%$). Among hard-leaved species, low-stemmed oak has the highest total carbon stock, i.e. 18,053.1 thousand tons due to its higher occurrence than other hard-leaved trees. Soft-leaved stands of the republic, leading both in the area and in stock, accumulate the largest total carbon stock, viz. 195,900.2 thousand tons, although, in terms of the average carbon accumulation per 1 ha, they are inferior to coniferous and hard-leaved forest-forming species in all ages. The ripening pine stands accumulate the greatest amount of carbon. The revealed amounts of carbon sequestration, its stocks and annual absorption by the biomass of coniferous and deciduous trees are presented in sections Nos. 3 and 6 of the Bashkortostan Republic's Forest Plan.

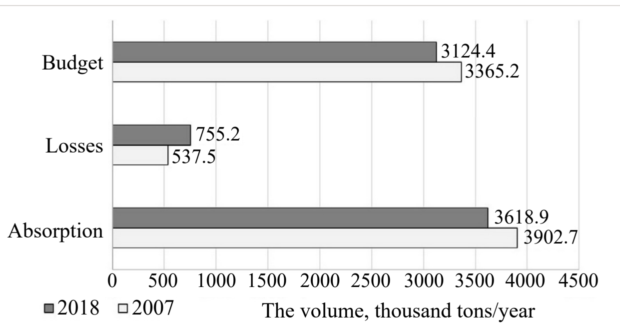

Figure 1. Changes in carbon stocks for 2007–2018

Many studies related to the assessment of carbon stocks using satellite imagery products (Abbas et al. 2020), the national forest inventory (Grüneberg et al. 2019), the collection of specific field data, or studies on the monetary assessment of carbon storage and sequestration in forests (Pache et al. 2021).

Conclusions

This study has considered the efficiency of forest ecological functions in carbon sequestration, which depends on the species, age structure, forest area and wood productivity. This study has determined that forests of the Ural region (the territory of the Republic of Bashkortostan) deposits carbon in the amount of 3,618.9 thousand tons/year. Among coniferous species, pine forests accumulate the largest amount of carbon, i.e. 58,384.3 thousand tons, of which young trees (1–40 years old) – 44.9, middle-aged (41–60 years old) – 91.5, ripening (61–100 years old) – 115, mature (101–120 years old) – 93.2 tons/ha. The largest volumes of annual carbon absorption are characteristic of young coniferous species. Larger areas and stocks of overmature soft-leaved stands are one reason for increased losses in the carbon budget in the forests of the republic in 2007–2018, which amounted from 537.5 to 755.2 thousand tons. In general, the difference between carbon absorption and its budget was 3,124.4 thousand tons/year. Soft-leaved species that dominate in the republic accumulate the largest total carbon stock, viz. 195,900.2 thousand tons, but in terms of the average level of carbon stock, they are inferior to the forests of coniferous and hard-leaved species. Carbon absorption by coniferous biomass averages 1,299.8 thousand tons/year, soft-leaved – 4,930.2 thousand tons/year and hard-leaved – 737.9 thousand tons/year. The greatest intensity of carbon absorption is observed in deciduous stands. Maintaining the carbon dioxide uptake by forests in 2018 is a strategic task of the forestry sector in the republic. It can be solved by compensatory reforestation.

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