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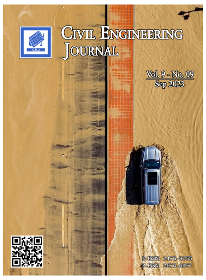

Carbon Sequestration Dynamics in Urban-Adjacent Forests: A 50-Year Analysis

A. A. Vais [1], P. V. Mikhaylov [1*], V. V. Popova [1], A. G. Nepovinnykh [1], V. N. Nemich [1], A. A. Andronova [1], S. K. Mamedova [1]

[1] *Reshetnev Siberian State University of Science and Technology, Krasnoyarskii Rabochii Prospect, 31, Krasnoyarsk, 660037, Russian Federation.*

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Abstract

Achieving carbon neutrality is crucial for urban ecosystems. Forests growing near cities largely determine the state of the environment in urban areas. The aim of the present research is to assess the carbon productivity dynamics in forests near Krasnoyarsk (a large industrial center) over a 50-year period in terms of carbon sequestration and conservation. The study was based on forest inventory conducted in Karaul'noe Forestry in 1972, 1982, and 2002 and forest inventory covering six forest compartments in 2022. The forest covers 3980 ha and consists of 52 forest compartments. The analysis was based on the assessment of carbon productivity dynamics and followed four levels of principles: forestry, structure, forest compartment, and forest stand. The research was based on forest fund dynamics, analyzing methods, long-term forest inventory, assessing carbon stock, and growing stock dynamics. Pine is the dominant forest-forming species that absorbs the most carbon in the study area. Pine is long-lived, covers a vast area, and has the highest carbon sequestration potential. At the forest structure level, the predominant carbon pools are mid-late successional and late successional stands dominated by pine, birch, and aspen. Forest compartment-level analysis revealed three trends in carbon sequestration: carbon balance, a decrease in carbon sequestration, and an increase in carbon sequestration. Notably, the prevailing trend is determined by changes in carbon sequestration by dominant forest-forming species (pine). Forest stand-level analysis showed that stands have become more and more uneven-aged. About 65% of total carbon stock is concentrated in mid successional, mid-late successional and late-successional stands, and 35% in young stands. The carbon sequestration rate decreases in forests with age. However, pine forests increase biological productivity and continue to successfully sequester carbon. Deciduous forests have lost their carbon sequestration potential, and the area they occupy is currently decreasing in the study area. The development of the young generation in pine stands suggests that the carbon sequestration potential in forests growing near the city will not decrease and may even increase due to climate change.

Keywords: Carbon Balance; Phytomass Pool; Carbon Sequestration; Forest Structure; Age Classes; Urban Area.

1. Introduction

Nowadays, a major issue in the development of large cities is air pollution from both stationary (industrial enterprises) and mobile (vehicles) sources [1]. Plantations near urban areas largely influence air quality [2]. These forests play a major role in absorbing CO_2 compounds produced by both vehicles and industrial activities. Forests act as a major carbon pool and also play a significant role in climate regulation. Some researchers state that temperate boreal forests (where the present study was carried out) account for about 32% of the total global stock of forest carbon [3]. Research studies showed that for the past decades, some changes in the carbon budget have been observed in the Russian

* Corresponding author: mihaylov.p.v@yandex.ru

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Federation (Russia). On the one hand, carbon stock has increased in the second half of the 2000s. The authors believe that this trend is related to reducing forest management intensity and the fact that carbon sequestration occurs unevenly across the country due to certain local features [4, 5]. On the other hand, dead organic matter, forest floor, and soil take a significant proportion (about 20%) of the total carbon stock in Russia [6]. The third relevant issue in carbon balance assessment is the uncertainty in the calculation methods. Zamolodchikov et al. [7] believe that it is necessary to prevent forest fires in Siberia and the Russian Far East more effectively to maintain the carbon sequestration rate in Russia. According to different methodological approaches, the carbon budget in Russian forests varies from 200 to 700 MtC per year^{-1}, which corresponds to an almost 3-fold difference in the estimates [8–10].

Carbon pool assessment depends on a number of factors, including species composition and the age structure of a stand [11]. For example, Utkin et al. [12] assessed carbon pools in pine forests in Russia in the 1990s and recorded an increase in carbon sink while the area occupied by the stands remained the same. It is explained by age-structure dynamics in forest stands (older trees have been replaced by young and middle-aged ones). What is more, logging intensity plays a significant role in calculating the carbon budget [12].

Carbon pool assessment largely depends on forest structure. It was found out that tree layers take for 32 to 73% of the total net production in the Komi Republic pine forests. Notably, in these pine forests, needles and stem wood take up a significant part of the net primary production in the tree layer [13]. In old pine forests in the Northern Urals, from 124 to 185 t*ha^{-1} of organic matter is accumulated in living plants, depending on site conditions. Forest stands dominate in carbon production, 86–94% [14]. According to Osipova & Bobkova [15], there is an increase in carbon pools in plant communities. At the mid-late successional stage, net carbon production decreases in pine forests. A system has been developed for predictive assessment of carbon sequestration by forest stand phytomass during the restoration of riparian forest in the Ili valley (Kazakhstan). Some researchers suggest using a model approach based on a system of regression equations in the predictive assessment of carbon sequestration by the phytomass of individual components of forest structure [16]. Mazurkin [17] stated that the patterns of phytomass distribution by forest structure components can only be determined by analyzing a significant number of research plots.

In waterlogged native old spruce forests, soil organic matter contains the most carbon [18]. According to Efremova and Efremova, in swamp forest ecosystems in Western Siberia, carbon pool dynamics is determined by certain local features determined by peat formation. The organic matter is mostly concentrated in the tree layer [19]. Nowadays, knowledge of bog complexes carbon pools has been accumulated [20–22].

Tundra ecosystems have their own features for absorbing and storing carbon. Maslov et al. [23] found out that the major ecosystem carbon pool (60–97%) is concentrated in thin soils that are determined by temperature gradients. Nagimov et al. [24] also revealed a number of features in the aboveground phytomass structure of V and Va bonitet class (low-productive) lichen pine forests in Western Siberia. The tree layer produces the most organic matter (60.5–88.3%). A significant part of organic matter is produced by the above-ground living vegetation (11.7–37.1%) and largely depends on forest fires. Some researchers have noted the influence of low temperatures on the biological and carbon productivity of pine forests.

Artificial stands are of higher productivity and absorb carbon more effectively than natural ones. Thus, one should consider the origin of a stand when assessing carbon productivity. Varaksin et al. [25] revealed that in closed-canopy, high-productive pine forests (I bonitet class) growing in the taiga/forest-steppe zone of Central Siberia, maximum biological productivity occurs at 120 years (411.5 t*ha^{-1}). The aboveground phytomass takes 86.8%, and the underground one takes 13.2% at this age. Klevtsov & Tyukavina [26] found that in artificial pine forests growing in the middle taiga zone of the Vologda Oblast, the biggest carbon pool is concentrated in stem wood (60–76%), followed by shoots of up to 0.8 cm diameter with needles (7–14%). Usoltsev et al. [27] compiled standards for determining the phytomass in artificial spruce stands in the Sverdlovsk Oblast at individual tree and forest stand levels.

Forestry practices largely influence carbon pools. For instance, studies conducted in Mediterranean pine forests showed that thinning boosts carbon sequestration rates [28]. The model approach allowed Li et al. [29] to plan a cutting age to optimize carbon sequestration and improve the associated economic and environmental benefits. Chinese scientists proved that forest inventory can reduce uncertainty and increase reliability in carbon estimates [30]. According to Kazakhstan researchers, the maximum amount of chemical compounds, including carbon, is concentrated in green biomass (needles) in pine forests near cities [31]. An analysis of the scientific literature indicates that the carbon budget of forest ecosystems is determined by numerous factors.

Carbon pool estimates are usually obtained by single measurements in a study area. What is more, the age trend is considered quite simply by selecting stands of different ages. Such an approach is time-saving and effective, but the reliability of the data collected may be questionable. Only long-term monitoring on permanent research plots can provide objective and adequate data. Forest inventories conducted in different periods are also a useful tool since they cover vast areas and allow for the consideration of an age trend. Therefore, there is a need for more active use of large-scale forest inventory data to assess both biological and carbon productivity and their dynamics over time. The present research was based on forest inventory conducted in the Karaul'noe Forestry located near Krasnoyarsk, Russia, for 50 years (1972–2022).

2. Materials and Methods

The research was based on the methodological approaches presented by Svalov [32], Liepa [33], and Sheingauz [34]. Svalov [32] described the method for compiling unified tables of stand productivity. The author covered the theory of forestry based on various management principles, forms of forestry, and methods for selecting forestry practices. Approaches to analyzing various forms of forest management based on forest inventory materials were shown. Liepa [33] conducted long-term studies to assess growing stock dynamics, considering tree species biological traits, habitat conditions, forest management regime, and stand-specific features. Sheingauz [34] suggested analyzing forest dynamics based on long-term forest inventory data. Here, all the methodological approaches [32–34] were used to study the carbon productivity dynamics based on state inventory data. Figure 1 shows the pattern that the present research followed.

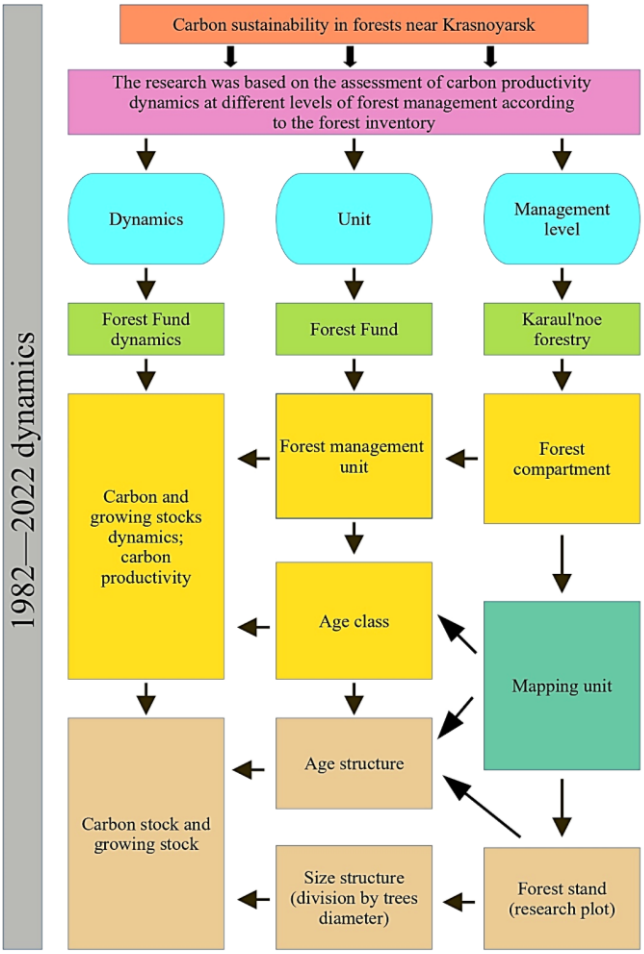


Figure 1. Block diagram describing the pattern for studying carbon sustainability in forests near cities

2.1. Study Area

The aim of the present study is to assess the dynamics of carbon sequestration potential in forest stands near Krasnoyarsk for 50 years in terms of carbon capture and storage. The following tasks were set to achieve the research aim:

- Use the dynamics in the forest fund, growing stock, and age trend as a methodological basis.
- Study carbon productivity, considering the structural features of forest stands.
- Evaluate the study area in terms of sustainable maintenance of its carbon sequestration potential.
- Calculate the carbon budget dynamics in forests near the city at different levels of management: forestry, species, forest compartment, mapping unit, and forest stand (research plot).

Krasnoyarsk is a large industrial city located in central Siberia along the banks of the Yenisey. The population of Krasnoyarsk is over one million. The city is situated in a hollow, which leads to the accumulation of air pollutants. Therefore, both raising the area of new plantations and forming a certain species and age structure of natural forests near the city are relevant. According to the State Report on the state and protection of the environment in Krasnoyarsk Krai in 2021 [35], 187.2 thousand tons of air pollutants affect air quality in Krasnoyarsk. Carbon monoxide (CO) takes up

53.3 thousand tons among all the air pollutants. The city is surrounded by a vast greenbelt that helps to improve environmental quality and absorb pollutants. In particular, the Karaul'noe forest of 3980 hectares is located near Krasnoyarsk (Figure 2). The study area is occupied by the main forest-forming species of the greenbelt (pine, birch, aspen, and fir). Krasnoyarsk covers an area of 35.390 hectares. Thus, the study area covers more than 10% of the urban ecosystem area.

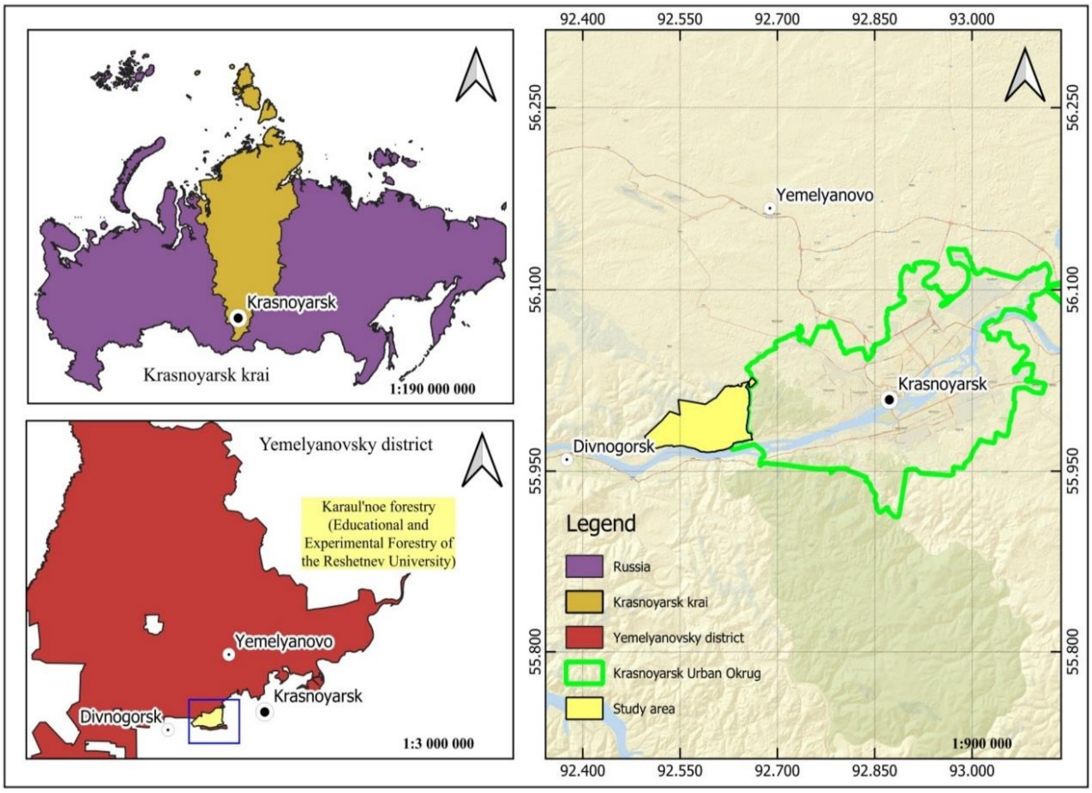


Figure 2. Study locations

Karaul'noe Forestry is an educational and experimental forestry of the Reshetnev Siberian State University of Science and Technology. Karaul'noe Forestry is located in the central part of Krasnoyarsk Krai in the Yemelyanovsky administrative district (longitude: 56.000, latitude: 92.600). Pine stands occupy watershed ridges and southern slopes along the Yenisei. The mean annual air temperature is 0.6 °C. The forests of Karaul'noe are mostly mid-late successional or late-successional (60.6% of coniferous stands and 68.6% of deciduous stands) (Figure 3). The study area is covered by mid-productivity forest (average bonitet class is II) that mostly represents the optimal species composition (61.1%) and habitat types.

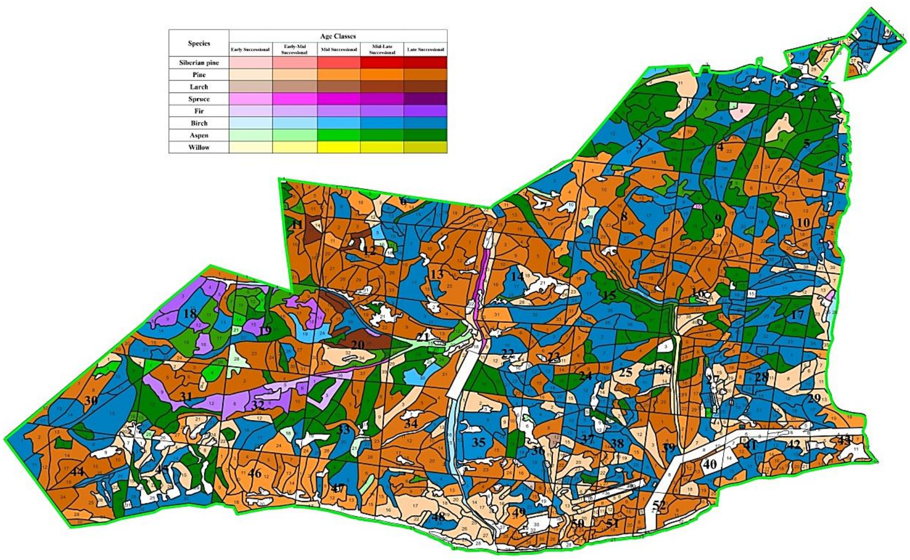


Figure 3. Species composition and age structure of the Karaul'noe forestry stands

2.2. Data Collection

The research was based on the forest inventory conducted in the study area in 1972, 1982, and 2002. Karaul'noe Forestry includes 52 forest compartments. The carbon budget was assessed by the forest compartments since the forestry division by forest compartments did not change, and the comparison allowed one to obtain reliable results. In 2022, an inventory of six forest compartments was carried out. Namely, No. 25 (includes 20 forest units), No. 26 (includes 23 forest units), No. 37 (includes 30 forest units), No. 38 (includes 31 forest units), No. 50 (includes 30 forest units), and No. 51 (includes 21 forest units). These six compartments were studied by forest units using satellite remote sensing (Figure 4).

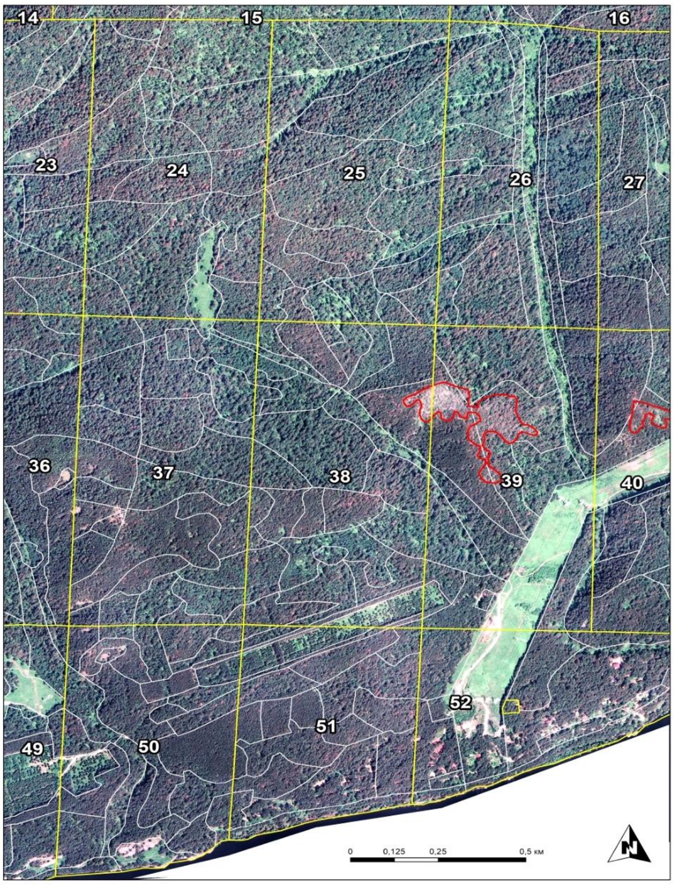


Figure 4. Satellite images of the studied forest compartments

The following stand characteristics for each forest unit were determined by conducting visual and instrumental forest inventory: composition, structure, origin, average height, age, average diameter, bonitet class (stand productivity), forest type, etc. Bitterlich sampling using randomly-located dimensionless points was performed to assess the growing stock.

The structure of carbon productivity was assessed at the individual pine stand level. Strip research plots in two pine-dominated forest units located in the same forest compartment (6 compartments, 12 strip research plots) were placed. On each research plot, at least 200 pine trees of more than 6.1 cm in diameter were measured. A field study was carried out following the Anuchin approach [36]. All the measured trees on each research plot were divided into diameter classes, and their variation series were obtained. Further calculations to obtain the structure of the stand carbon pool were performed using volume conversion coefficients [37]. The Karaul'noe forestry stands were divided into the following groups according to the dominant species: pine, birch, aspen, fir, larch, Siberian pine, and others. Each group was also divided into age classes: early successional, early-mid successional, mid-sequenceal, mid-late successional, and late successional. After performing all the calculations, stand characteristics were put in united tables for each forest compartment (the data in these tables was also grouped by dominant species and age classes).

2.3. Data Analysis

The method of regional assessment of forest carbon budgets was used to assess the aboveground phytomass carbon in the stands [38]. The IPCC Guidelines provide the methodology to estimate forest carbon stock and forest carbon budget in four pools: 1) phytomass of a forest stand (tree layer); 2) dead wood (snag and coarse woody debris); 3) forest floor; 4) soil organic matter. The present research is focused on assessing the tree layer phytomass pool. The study area belongs to the Eastern Siberia middle taiga zone.

The growing stock value and conversion coefficients were used to assess the ratio of above-ground phytomass carbon stock to the growing stock. Conversion coefficients are measured in $tC*m^{-3}$. The conversion coefficients let one calculate the entire above-ground phytomass (including stems, branches, needles, and leaves) using the growing stock. Here, the calculations based on conversion coefficients determined for dominant tree species considering stand age classes were performed. Equation 1 was used to calculate the carbon stock in forest stand above-ground phytomass by age classes of the dominant species in the study area:

$$CAP_{ij} = V_{ij} \times KAP_{ij} \quad (1)$$

where *CAPij* is above-ground phytomass carbon stock in a stand of age class i dominated by j tree species (tC); *Vij* is growing stock in a stand of age class i dominated by j tree species (m^3*ha^{-1}); *KAPij* is conversion coefficients to assess above-ground phytomass carbon stock in a stand of age class i dominated by j tree species ($tC*m^{-3}$) (the conversion coefficients are shown in Table 1 [39]).

Table 1. Conversion coefficients ($tC*m^{-3}$) for calculating the carbon stock in forest stand above-ground phytomass based on the growing stock in Eastern Siberia middle taiga zone

Dominant species	Zone	Age classes				
		early successional	early-mid successional	mid successional	mid-late and late successional	early successional
Pine	2	0.343	0.273	0.277	0.279	2
Spruce	2	0.390	0.301	0.282	0.271	2
Fir	1-3	0.323	0.254	0.217	0.219	1-3
Larch	2	0.351	0.364	0.368	0.353	2
Siberian pine	1-3	0.299	0.248	0.241	0.300	1-3
Birch	2	0.342	0.348	0.307	0.293	2
Aspen	1-3	0.266	0.273	0.251	0.287	1-3
Other deciduous species	1-3	0.318	0.272	0.274	0.271	1-3

Note. Zones: 1 – northern taiga, 2 – middle taiga, 3 – southern taiga and more southern climate zones

Subsequently, the obtained average values by years were summarized in tables for each forest compartment: area, age, height, diameter, bonitet class, density, growing stock per ha, total growing stock in the forest unit, carbon stock per ha, and total carbon stock in the forest unit. The analysis was level-based: forestry, forest structure, forest compartment, forest unit, and forest stand (Figure 5).

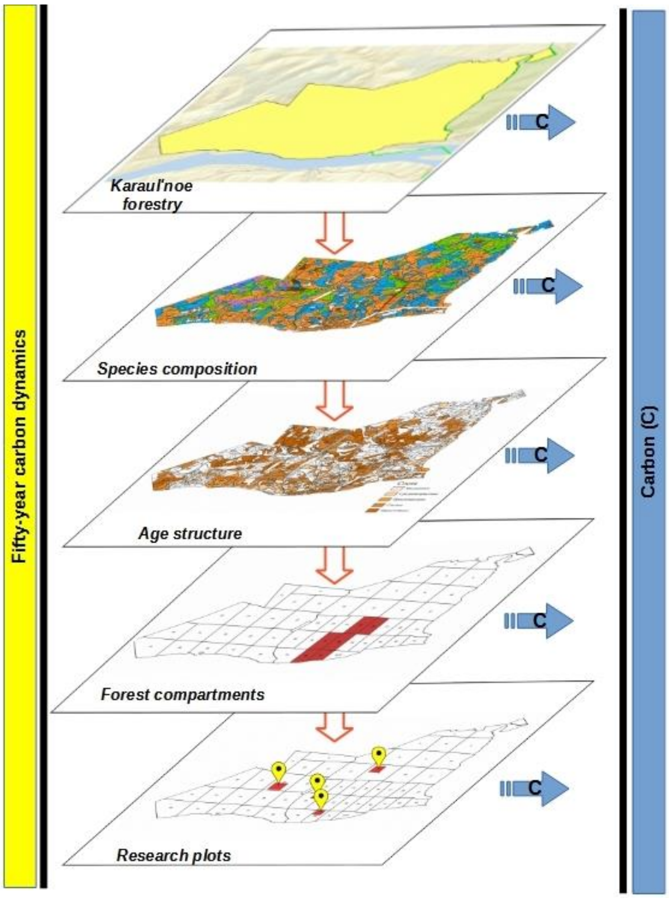


Figure 5. Levels used to analyze 50-year carbon stock dynamics in the Karaul'noe forestry (1972-2022)

3. Results

3.1. Carbon Sequestration Dynamics Assessment at the Forestry Level

Forest inventory confirmed that carbon sequestration has increased in the Karaul'noe forestry. For example, the total carbon stock was 164095 tonnes of carbon (tC) in 1972, 207780 tC in 1982 and reached 228154 tC in 2002 (Figure 6).

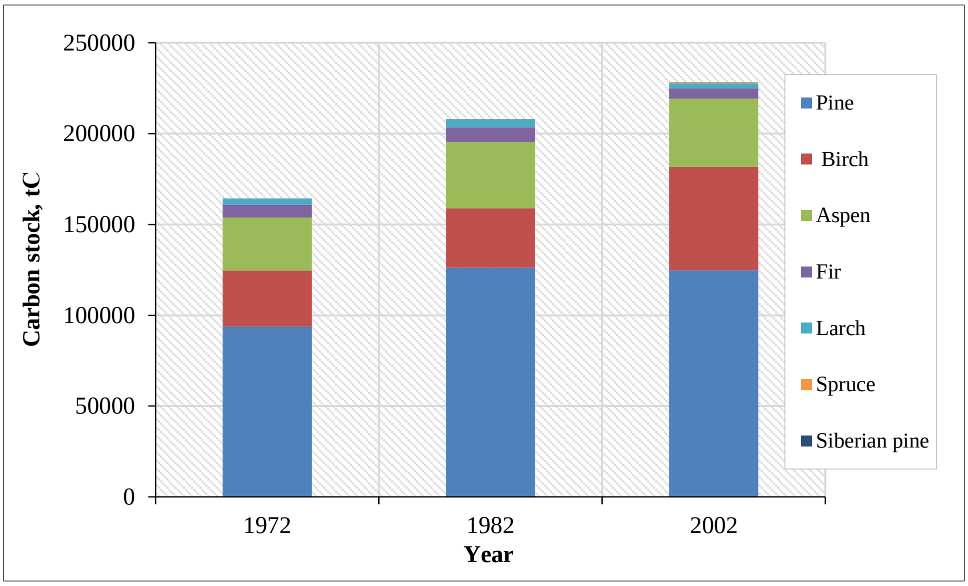


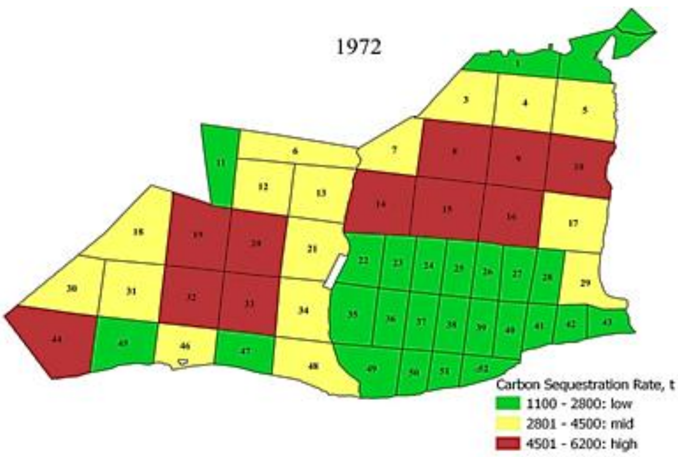
Figure 6. Karaul'noe forestry carbon stock divided by forest inventory periods and species composition

There was an intensive growth in the carbon budget in 1972–1982 due to the species composition and age structure of the forest stand (pine and aspen sequestrated carbon at a high rate). In 1982–2002, the carbon sequestration rate declined significantly. A slight increment was provided by birch during this period.

3.1.1. Species Composition

Pine is the dominant forest-forming species in the study area. Thus, pine stands act as a major carbon pool in Karaul'noe forestry (93793 tC in 1972, 126170 tC in 1982, and 124736 tC in 2002). Birch stands are the second (30858 tC in 1972, 32695 tC in 1982, 56857 tC in 2002). The third biggest carbon pool is aspen stands (29145 tC in 1972, 36464 tC in 1982, and 37659 tC in 2002). The remaining species (fir, Siberian pine, spruce, and larch) do not have a significant impact on carbon sequestration in the study area. However, it should be noted that the area of so-called dark coniferous forests (Siberian pine/fir/spruce-dominated stands) has been increasing.

At the forest compartment level (most are 1×0.5 km and 50 ha), the Karaul'noe forestry was divided into three groups by carbon sequestration rate: low (1100–2800 tC), mid (2801-4500 tC), and high (4501–9600 tC) (Figure 7). Figure 6 shows that the number of forest compartments with a high carbon sequestration rate has been growing (11 forest compartments in 1972, 21 forest compartments in 1982, and 26 forest compartments in 2002). These data prove that forests near the city act not only as carbon absorbers but also as carbon stores since they both sequester and emit carbon.



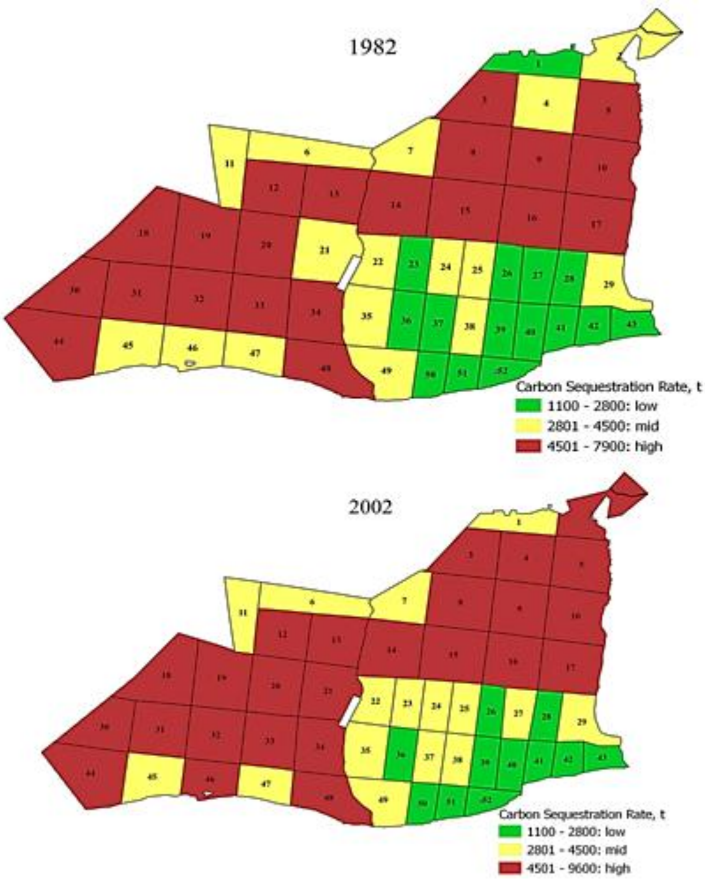


Figure 7. n sequestration dynamics in the Karaul'noe forestry from 1972 to 2002

3.1.2. Age Structure

The conducted forest inventory divided all the data by age classes: early successional, early-mid successional, mid successional, mid-late successional, late successional. An analysis of stands dominated by pine, birch, and aspen was performed since they have the highest carbon sequestration rate (Table 2).

Table 2. Carbon stock in dominant forest-forming species stands by forest inventory periods and age classes

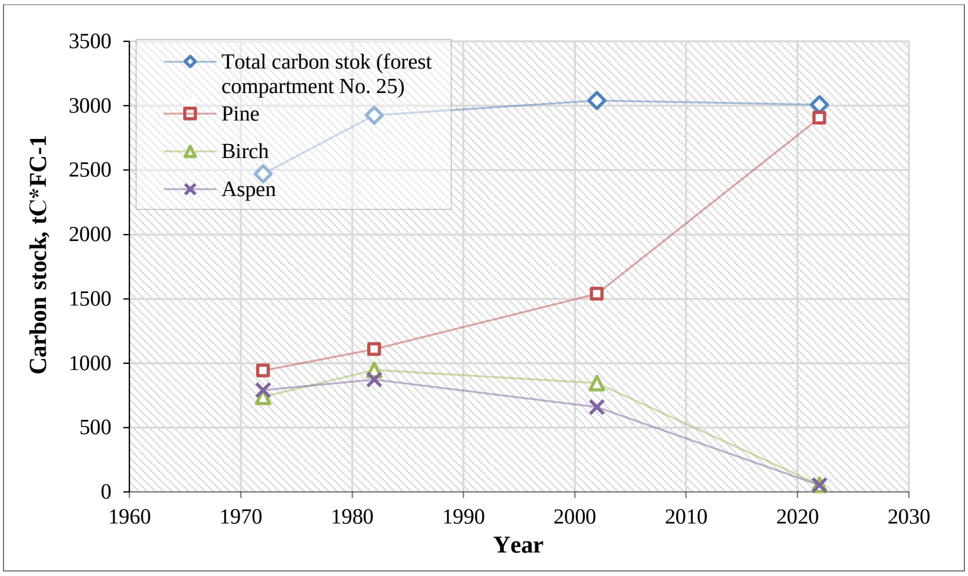
Age class	Carbon stock (tC)		
	1972	1982	2002
Pine-dominated stands			
Early successional (up to 40 years)	7845	5084	184
Early-mid successional (41-80 years)	42509	33925	29407
Mid successional (81-100 years)	19349	56196	19075
Mid-late successional (101-140 years)	7302	8463	42514
Late successional (141 years and above)	16788	22503	33557
Birch-dominated stands			
Early successional (up to 20 years)	-	-	3
Early-mid successional (21-60 years)	19796	5620	234
Mid successional (61-70 years)	10568	18307	1112
Mid-late successional (71-90 years)	493	7910	5845
Late successional (91 years and above)	-	858	49662
Aspen-dominated stands			
Early successional (up to 20 years)	148	16	111
Early-mid successional (21-50 years)	12929	3315	551
Mid successional (51-60 years)	11026	15466	823
Mid-late successional (61-80 years)	4650	14785	4916
Late successional (81 years and above)	393	2884	31257

Carbon dynamics in pine stands from 1972 to 2002 showed a decrease in the carbon pool in young stands (7845-5084-184 tC) and in middle-aged stands (42509-33925-29407 tC). Multidirectional changes in carbon stock were typical for mid successional pine stands (19349–56196–19075 tC). The carbon sequestration dynamics are driven by a change (mainly a decrease) in the area covered by the stands of these age classes. Carbon stock dynamics showed an increasing trend in mid-late successional (7302-8463-42514 tC) and late successional (16788-22503-33557 tC) age classes. There is a trend towards an increase in the area covered by pine stands of these age classes.

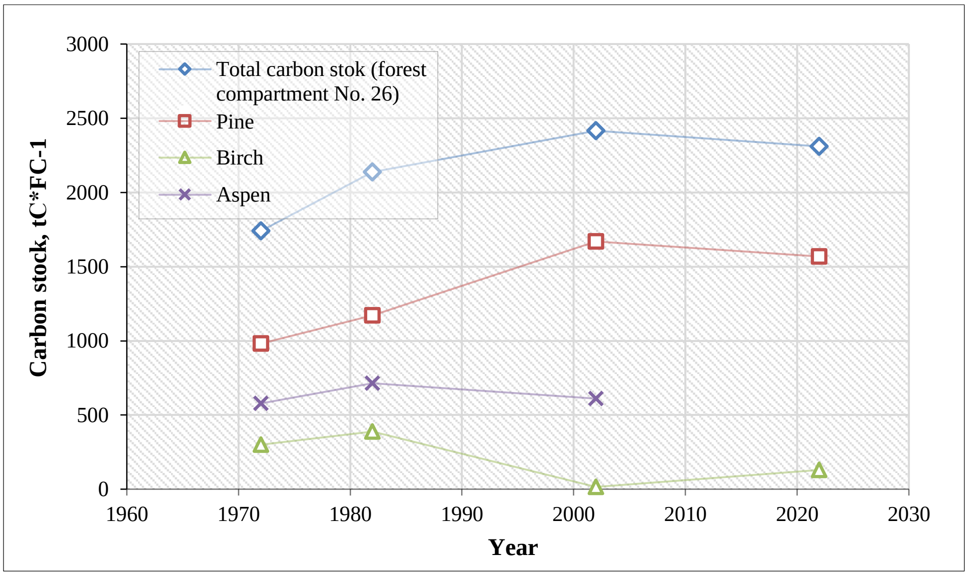
Birch-dominated stands were characterized by a downward trend in carbon sequestration in early-mid successional stands (19796-5620-234 tC) and mid successional stands (10568-18307-1112 tC). Carbon pools increased in mid-late successional and late successional age classes. The dynamics are also determined by the age structure and spatial distribution of birch stands. Carbon stock decreased in early-mid successional aspen-dominated stands (from 12929 to 551 tC). Late successional aspen stand carbon pools increased (from 393 to 31257 tC). Multidirectional trends in carbon dynamics were observed in early successional, mid successional, and mid-late successional aspen-dominated stands. The dynamics are influenced not only by the age structure and spatial distribution of aspen stands but also by their health status (some aspen stands die even at the early successional stage).

3.2. Carbon Sequestration Dynamics Assessment at a Forest Compartment Level

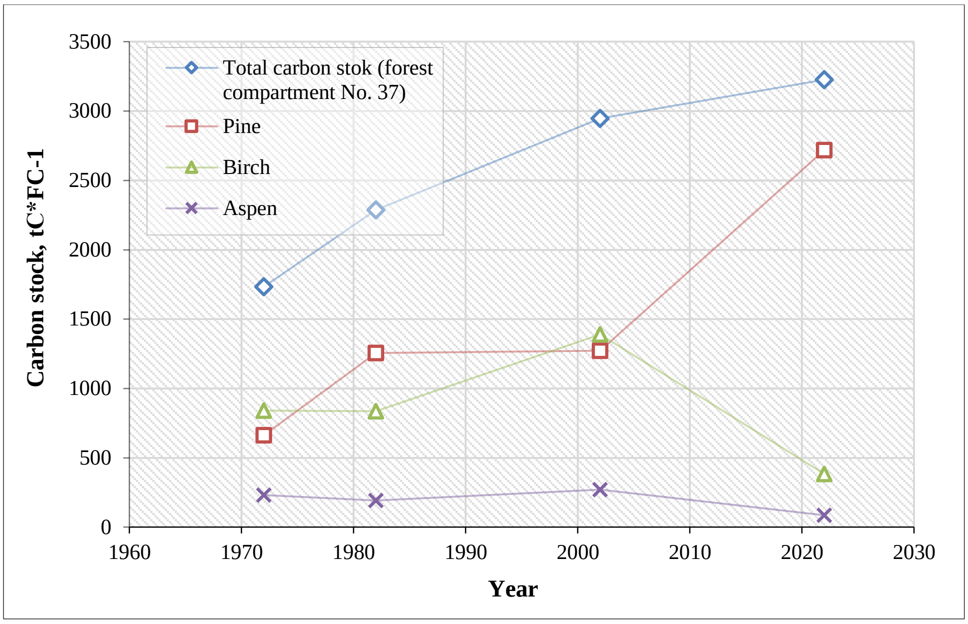
Forest compartment-level analysis lets one identify the prevailing trends in carbon dynamics in forest-forming species in forest sites of at least 50 ha (Figure 8). The data obtained in six forest compartments were analyzed by inventory periods (1972–1982, 2002–2022). Both total and species-depended dynamics of carbon sequestration by dominant forest-forming species were studied. As a result, three patterns in carbon dynamics in the studied forest compartments were revealed: carbon balance, Figure 8-a (forest compartment No. 25); decrease in carbon sequestration, Figure 8-b (forest compartment No. 26); and increase in carbon sequestration, Figure 8-c (forest compartment No. 26).



(a) Forest ecosystem carbon balance



(b) Decrease in forest ecosystem carbon sequestration

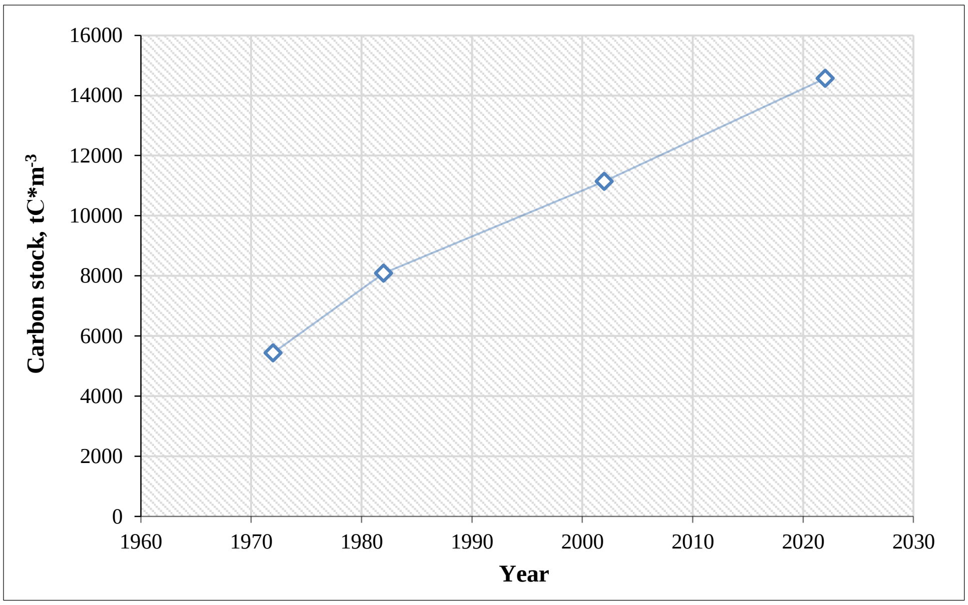


(c) Increase in forest ecosystem carbon sequestration

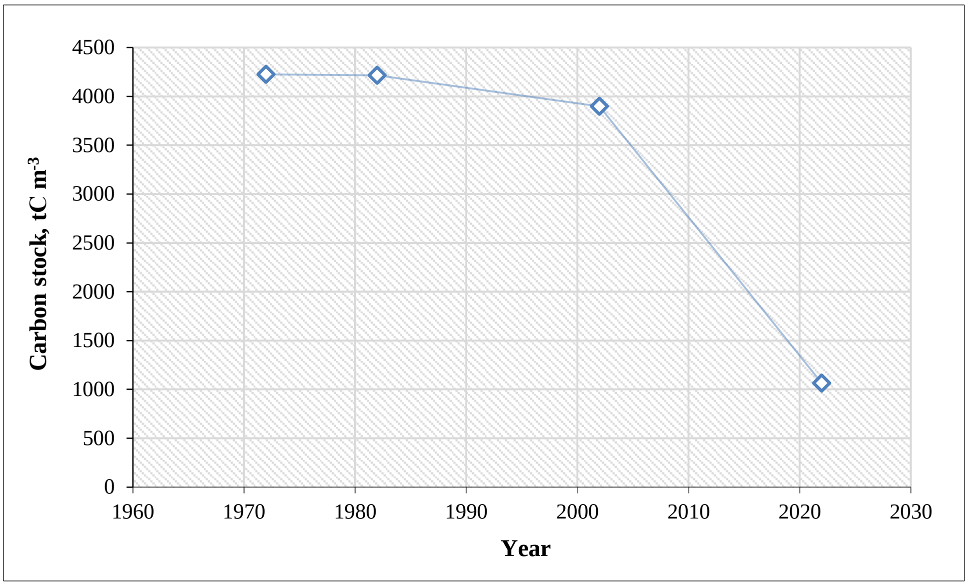
Figure 8. Carbon dynamics in forest compartments "Note: FC – forest compartment area (ha)"

The carbon balance in the Karaul'noe forestry ecosystem is reached by a multidirectional trend combination: the growth of the main forest-forming species (pine) and the decrease in the carbon pool of other species. The total decline trend in carbon stock arises from the decrease in the carbon pool of all the forest-forming species in the study area. The increase in carbon pools at forest compartment level is explained by an increase in the growing stocks of the main forest-forming species (pine), despite a decrease in the carbon sequestration rate in deciduous species.

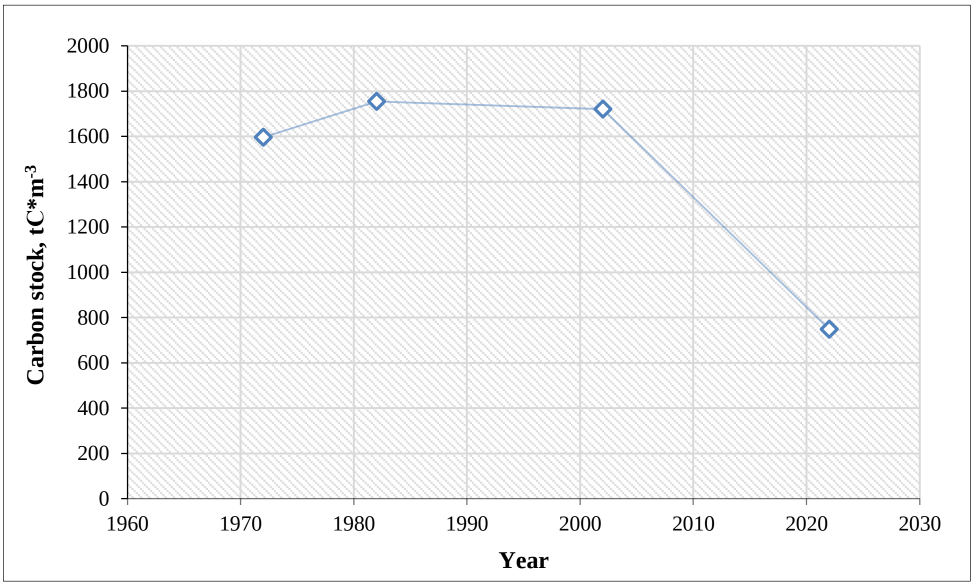
An increase in carbon sequestration rate in the pine stands within the six studied forest compartments was recorded. However, the increase did not follow the balance trend of pine stands throughout the entire Karaul'noe forestry (Figure 9-a). These six forest compartments are situated along the bank of the Yenisey. What is more, these forest stands grow on former agricultural lands. All these contribute to a local increase in stem and carbon productivity in these six forest compartments.



(a) Carbon stock dynamics in pine-dominated stands



(b) Carbon stock dynamics in birch-dominated stands



(c) Carbon stock dynamics in aspeb-dominated stands

Figure 9. Carbon stock dynamics in six forest compartments based on forest inventory conducted in 1972, 1982, 2002, and 2022. Note: FC – forest compartment area (ha)

In birch and aspen stands, there was a trend of a sharp decrease in carbon stocks in the last 20 years (Figures 9-b and 9-c), which was due to the stand dieback. Nevertheless, analysis at the forestry level indicated an increase in carbon sequestration by deciduous stands, especially birch-dominated ones (excluding data for 2022). The carbon sequestration rate reduction was especially evident in the last 20 years. An analysis of the dynamics for 2002–2022 revealed the onset of a negative trend in carbon emissions from deciduous plantations.

3.3. Carbon Sequestration Dynamics Assessment at a Forest Stand Level

At the forest stand level, carbon stock was assessed using the phytomass of an individual tree. The data were obtained by the Institute of Forestry of the Siberian Division of the Russian Academy of Sciences for Central Siberia. The study of age structure based on increment core analysis showed that pine forests have an uneven age structure. An example of a pine-dominated stand where a 0.30 ha strip research plot was placed is as follows (forest compartment No. 51, forest unit No. 13). The stand species composition includes 60% pine and 40% birch; fir and spruce occupy 0.1-2.4% of the total growing stock on the research plot. The stand has a high relative density (1.34), and its total growing stock is 669 m^3/ha. The age of individual trees in the stand varies from 50 to 140 years. The other forest stands where strip research plots have been placed are of similar or close characteristics. Figure 10 shows the stand diameter structure (according to timber cruising) to let one assess the quantitative structure of the studied stands: the distribution of trees by diameter classes (Figure 10-a) and the distribution of carbon pools by diameter classes (Figure 10-b).

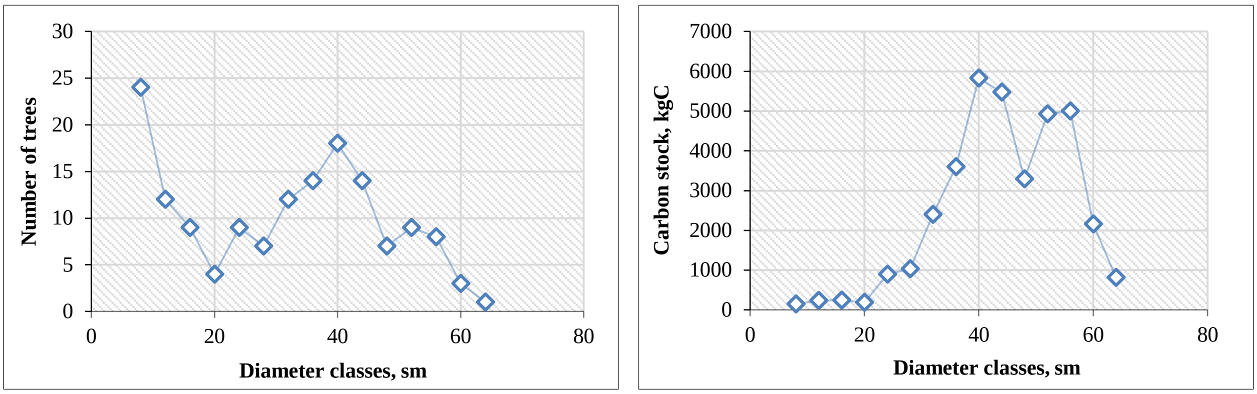


Figure 10. Trees and carbon distribution by diameter classes

A slight unevenness in the pine stand age structure indicates the presence of small- and large-size tree generations (Figure 9-a). Since large trees (diameters of 40–52 cm) sequester the most carbon, the carbon pool distribution by diameter classes is uniform (Figure 9-b).

The trees in the stands were divided into three generations: I (diameter of 6.1-20.0 cm); II (diameter of 20.1-48.0 cm); and III (diameter of 48.1-64.0 cm). Notably, the young generation will turn older and continue to sequester carbon. Currently, however, the I generation role in carbon sequestration is low (Figure 8-b). Here, carbon stock distribution (%) was divided by diameter classes and age classes (Table 3). The I generation includes 32.5% of all trees but only 2.3% of carbon. At the same time, the carbon sequestration potential of this generation is high. The main carbon pool is concentrated in the II generation (53.6% of trees and 35.6% of carbon stock).

Table 3. Distribution of trees, carbon and age classes by diameter classes

Diameter class (cm)	**up to 6 cm**	**6.1-20.0**	**20.1-48.0**	**48.1-64.0**
Number of trees (%)	neglected	32.5	53.6	13.9
Carbon stock (%)	neglected	2.3	62.1	35.6
Age (years)	up to 50 years old	51-80	81-140	120-180
Age class	early successional, early-mid successional	mid successional	mid successional, mid-late successional	mid-late successional, late successional

4. Discussion

An important factor in any urban ecosystem is carbon balance. Unfortunately, urban plantations are not enough to achieve carbon balance. Forests near cities can absorb a significant amount of industrial and vehicular carbon and help improve environmental quality.

The methodology for estimating carbon sequestration over time makes it possible to reveal carbon sequestration dynamics. To study such a dynamic, it is advisable to use GIS technologies and the data obtained during forest inventory (Figure 6). By doing so, one can indicate processes occurring in the forest fund and productivity dynamics. The division of a study area into more homogeneous units (forestry-set of forest compartments-forest compartment-forest stand) provides an opportunity to identify processes in carbon sequestration that are difficult to identify at the large-scale level (Figures 4, and 7 to 9).

The present research proved that the carbon sequestration rate has been gradually decreasing in Karaul'noe forestry (Figure 5) due to structural changes that determine the intensity of carbon sequestration. Carbon sequestration potential depends on species composition, age structure, size structure, and spatial distribution of the stands (Figure 3).

The authors can state a decreasing trend in the major carbon pool (pine-dominated stands) according to forest inventory data (1972-1982-2002). The age structure of birch stands contributed to a significant increase in the carbon sequestration rate there. Aspen stands are stable in terms of carbon stock. The analysis of carbon sequestration in Karaul'noe forestry revealed that the carbon sequestration rate depends on the species composition and the proportion of land covered by coniferous and deciduous stands.

The age dynamics indicated the gradual aging of pine-dominated stands. In 1972, mid successional pine stands acted as a major carbon pool; in 2002, it was mid-late successional pine stands. Nowadays, late successional pine stands have the highest carbon sequestration rate. In general, the trend is unfavorable for carbon sequestration, but it corresponds to the natural aging of pine stands in Karaul'noe forestry. Currently, the process of dieback of individual trees in birch and other mixed plantations continues. Late successional birch and aspen stands have the highest carbon sequestration rate. The age structure determines the spatial distribution of stands by groups. Thus, the carbon sequestration potential of particular tree species depends on age.

Pine (a tree species with the highest carbon sequestration rate) plays the most significant role in maintaining carbon balance. Moreover, there is a decrease in the area covered by deciduous carbon absorbers (birch and aspen) (Figure 7-a). Pine and birch stand also start absorbing less carbon with age, inducing the overall decrease in carbon sequestration in the study area (Figure 7-b). However, there has been a sharp increase in carbon sequestration by pine stands during the last 20 years (2002–2022), which contributed to the increase in carbon sequestration in the study area (Figure 7-b).

The forest stand-level analysis revealed the heterogeneity of forest sites (primarily in terms of the pine stand age structure), which determined the structure of the carbon stock. The presence of pine stands among the younger generation is a factor contributing to the high carbon sequestration potential in Karaul'noe forestry. Net ecosystem production (NEP) varies significantly in forests depending on dominant tree species, stand age, and environmental factors. Scientists from other countries also state that forest carbon stock increases with age. For example, remote sensing allowed Chinese scientists to indicate that despite the decrease in the area of green spaces, the total area of above-ground biomass is increasing [40].

It is of high importance to study the structural features of a study area. There is research proving that it is the structure of land-use categories that has a significant impact on carbon sequestration [41]. Researchers believe [42] that aggregate green zones (urban plantations and forests near urban areas) with a high carbon sequestration rate play a crucial role in carbon cycling in urban areas. The present study showed a decline in resilience of forests near cities due to their health status; deciduous stand decline and other negative processes; and an increase in urban air pollution level due to a significant rise in the number of cars. Previous studies conducted in aspen forests in the study area revealed a high growth rate in early-successional aspen stands. However, along with biomass increment, a decline in resilience and wood loss occur in aspen stands with age due to natural and pathogen-induced mortality. Carbon emissions in aspen stands increase from 1 tC/ha at 50 years to 12 tC/ha at 80 years [43].

Carbon stock increments over the past 20 years may be caused by climate change, which is confirmed by Norwegian scientists [44]. The scientists studied spruce (a dominant species in Europe). It was revealed that air temperature was the most important determinant of NEP fluctuations, followed by global radiation and stand age, while precipitation made a very limited contribution to the model. There has been an increase in both growing season length and air temperature near Krasnoyarsk, especially in 2002–2022 [45]. The results obtained make it possible to determine the future development of forests near the city in terms of carbon sequestration. The authors believe that forests near Krasnoyarsk will maintain their resilience and continue absorbing carbon at a high rate due to the following factors: the forests are of high timber and carbon productivity, the stands are unevenly aged, and pine forests cover the largest area.

The data obtained during forest inventory is somewhat subjective since not only an instrumental but also a visual assessment has been made. They are established on the basis of visual-instrumental taxation. The advantages of assessing carbon productivity based on forest inventory data include the following: it covers a large area, the data can be analyzed at different levels, the data can be associated with a forest compartment map, and observations are long-term (since the inventory is carried out every twenty years).

5. Conclusions

The analysis of the data obtained during the long-term forest inventory (from 2002 to 2022) made it possible to draw a set of conclusions on the carbon productivity of forests growing near the large industrial city of Krasnoyarsk, Russia.

- The research was based on the methods of analyzing forest fund dynamics, long-term forest inventory, and the assessment of both growing stock and carbon stock dynamics.
- The theoretical significance of the research is associated with the assessment of three interrelated processes: the forestry management level, structure, and dynamics. The use of these components made it possible to determine the carbon sustainability of forests.
- The use of a level-based approach in studying the long-term dynamics of carbon productivity lets one detail the carbon sequestration-related processes in the study area.
- Pine is the dominant forest-forming spice and also the major carbon absorber in forests near Krasnoyarsk, Russia. Pines are long-lived and cover a vast area. Moreover, pine stands have the highest carbon sequestration rate. Deciduous stands (aspen and birch) are also important in carbon sequestration. Other stands (fir-, Siberian pine-, spruce-, and larch-dominated) do not have a significant impact on the carbon sequestration in the study area.
- At the level of species composition, mid-late successional and late successional stands of the main forest-

forming species (pine, birch, and aspen) have the highest carbon sequestration rate. On the one hand, such a trend contributes to the structure of uneven-aged pine stands. On the other hand, it implies a dieback of the deciduous stands.

- At the forest compartment level, three trends in carbon sequestration were identified: carbon balance, a decrease in carbon sequestration, and an increase in carbon sequestration. Notably, the overall trends are related to the dynamics of carbon sequestration by the dominant species (pine stands).
- The study of the structure of pine stands showed that they have become more and more uneven in terms of age structure. About 65% of all carbon is accumulated in mid successional, mid-late successional and late successional stands, and 35% in the stands of younger generations.
- The carbon sequestration rate decreases with the natural aging of stands. Pine stands, however, increase biological productivity and continue to successfully sequester carbon. Deciduous stands have lost their carbon sequestration potential, and the area covered by these stands is currently decreasing.
- The development of the young generation in old pine forests lets one suggest that the carbon sequestration potential in forests near cities will not decrease and may even increase due to climate change.

The presented approach lets one estimate a forest carbon budget based on the data obtained during long-term forest inventory. The use of GIS technologies makes it possible to visualize and detail processes at different levels within a study area structure. Continued monitoring of the carbon sustainability of the forest ecosystem will prevent possible negative processes associated with climate change and an increase in the atmospheric concentrations of greenhouse gases, especially in urban areas.

6. Declarations

6.1. Author Contributions

Conceptualization, V.A.A. and M.P.V.; methodology, V.A.A. and N.A.G.; formal analysis, V.A.A.; investigation, V.A.A., N.A.G., and N.V.N.; data curation, P.V.V., A.A.A., and M.S.K.; writing—original draft preparation, V.A.A. and M.P.V.; writing—review and editing, V.A.A. and M.P.V.; visualization, N.A.G. and S.O.A.; funding acquisition, M.P.V. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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