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Needles carbon pool structure in pine stands growing on abandoned farmland in subtaiga/forest-steppe zone of Central Siberia

Andrey Vais, *Victor* Nemich, *Sevinch* Mamedova*, *Pavel* Mikhaylov, and *Artem* Nepovinnykh

Reshetnev Siberian State University of Science and Technology, Krasnoyarsk, 660037, Russia

Abstract. Studying green biomass carbon pool makes it possible to assess carbon sequestration potential of both forests stands and individual trees. Such a study is highly relevant considering the fact that pine stands are replacing abandoned farmlands in Central Siberia. The criterion used to differentiate pine forests was the stand density. Modelling the stands structure (in terms of number of trees and needles carbon pool) considering trees diameter, showed that the Gaussian function is the most adequate. The stands diameter structure differs from the needles carbon pool structure. Trees average for a specific stand sequester the most carbon by their needles. Thus, forest managers should focus on saving medium-sized pine trees. In recent year, there has been a gradually increasing global temperature, which influence both the growth rate and the structure of forest stands. As a result, an equation was obtained that consider the change in the average diameter, standard deviation and maximum temperature extremes.

1 Introduction

Pine forests are the primary oxygen producers that absorb the most carbon in boreal forests ecosystems in Central Siberia. Notably, pine needles play a crucial role in these processes. Studying green biomass carbon pool considering trees diameter and needles mass makes it possible to assess carbon sequestration potential of both forests stands and individual trees. Such a study is highly relevant considering the fact that pine stands are replacing abandoned farmlands in Central Siberia.

Some research dedicated to green biomass carbon pool in forest stands have already been conducted. For example, it was found out that in coniferous forests growing in the Krasnoyarsk-Kansk forest-steppe zone, needles mass took from 28.6 to 57.1 % of the whole biomass [1]. Mamonov [2] stated that in the Irkutsk Oblast, the mass of needles was minimal in high-density pine stands (density of 0.8-1.0) in all age classes. What is more, it was revealed that needles took 34-36 % and branches took 64-66 % of the total tree crown mass [3].

Similar patterns have been revealed in other regions of the Russian Federation. For instance, Kunnikov and Feklistov [4] conducted a research in pine forests of the European

* Corresponding author: mamedova_ceva@mail.ru

North and stated that the share of green biomass stock in the total biomass increased with age from 9 to 13 %. It was found out that in the Middle Urals the mass of needles varied from 19.2 to 87.5 % in the total mass of crowns [5]. The share needles take in the total biomass increases with a decrease in trees diameter and age and also with an increase in height and a decrease in bonitet class. The mass of needles increases sharply in young forest stands, then comes its climax stage, after which it slightly decreases.

Startsev [6] studied the relationship between the mass of needles and pine forest stands characteristics in the coniferous/temperate broad-leaf forest zone. In pine trees, the mass of needles is closely related to tree diameter and the crown spread. Regional tables were constructed for the Nizhny Novgorod Oblast [7] since the mass of needles in pine tree crowns was significantly bigger there than in other regions of Russia. Nagimov [8] revealed a high correlation between green biomass fractions and a forest stand characteristics. In particular, the correlation between masses of crowns and needles and a relative cross-sectional area (G1.3/H) and crown diameter. It was found out that the mass of crown in trees of identical age and diameter decreases with increasing height. In trees of the same size, the mass of all crown fractions decreases with age, which can be explained by the age-related change in the social status of a tree.

In recent years, foreign scientists have been using model approaches to assess biomass of individual trees and entire stands. Mainly, the following input predictors are used in such regression models: the age of forest stand and the habitat characteristics of individual research plots [9]; remote sensing data [10]; tree diameter and height [11]; laser scanning methods [10].

2 Materials and methods

The research was carried out in the Karaul'noe forestry that is Educational and Experimental Forestry of the Reshetnev Siberian State University of Science and Technology (Reshetnev University). The study area belongs to the subtaiga/forest-steppe zone of the Central Siberia. Research plots were placed in pine forests situated on the second terrace of the Yenisei river on abandoned agricultural land (Figure 1). Table 1 shows the main silvicultural and forest inventory details from our studies.

All quantitative indicators of phytomass and carbon stock were calculated using Microsoft Excel and STATGRAPHICS softwares.

There are 10 research plots placed in the study area to conduct monitoring in pine forests. Some of them were placed in 1994 and then re-measured in 2021 (RP No.10). The studied pine stands are pure and even-aged (68-70 years) since they have occupied the abandoned farmlands. The average tree height varied from 17.0 to 24.4 m. The average tree diameter varied from 16.9 to 29.1 cm. The main criterion to differentiate the pine forests was their density (stocking, absolute and relative density) (Table 1). The stocking ranged from 296 to 2787 trees per ha. The combination of indicators determined the variation in growing stock from 180 to 640 m^3/ha.

The assessment of the needles mass was based on the trees measurements (diameter) and the local table of the average weight of freshly picked needles (kg) for trees of various diameter, depending on the pine stand canopy density constructed for the Krasnoyarsk Krai [12] (Table 2).

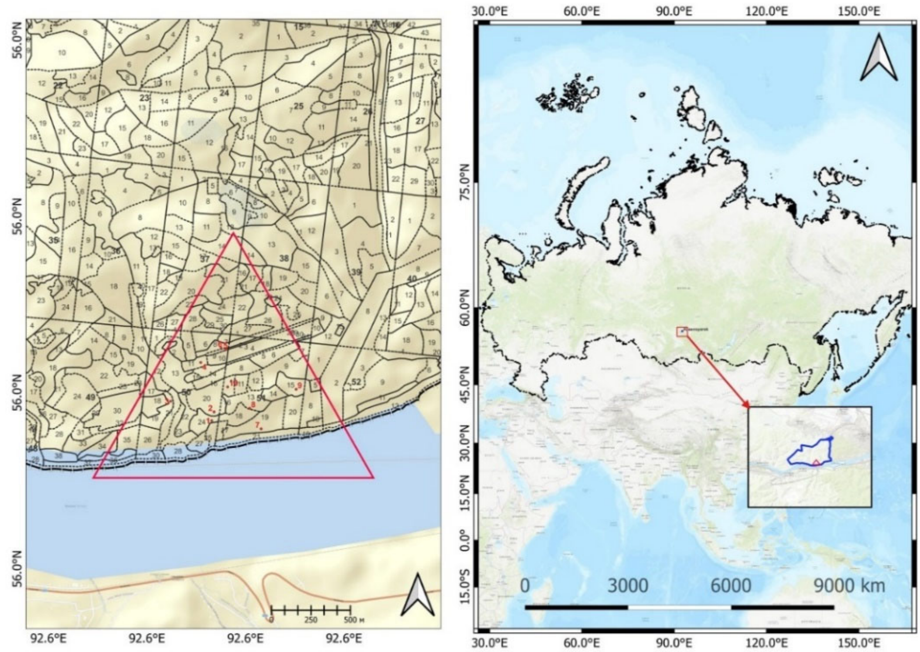


Fig. 1. Scheme of the research area and sample plots location.

Table 1. Forest inventory of the studied pine stands.

Research plot	Species composition	Age, years	H, m	D, cm	Basal area, m^2/ha	Relative density	Stocking, trees/ha	GS, m^3/ha
1	10P	68	22.5	20.1	54.10	1.53	1730	605
2	10P	70	23.2	20.9	55.64	1.56	1723	621
3	10P	70	24.4	22.7	46.50	1.29	1152	560
4	9P1B	70	22.9	29.1	19.77	1.20	698	484
5	10P	60	21.8	21.1	43.33	1.25	1245	454
6	10P	60	17.0	14.5	45.98	1.40	2787	410
7	10P	69	22.5	19.5	62.71	1.83	2105	640
8	10P	68	18.8	16.9	42.40	1.25	1885	424
9	10P	70	18.7	20.0	32.36	0.95	1032	312
10	10P	97	23.6	23.6	52.72	1.46	1207	576

Note: Scots pine (P) – *Pinus sylvestris* L.; Birch (B) – *Betula pendula* Roth; here we present the average stand-wide values of age, height (H) and diameter (D); GS – growing stock, m^3/ha

Table 2. The average weight of freshly picked needles (kg) for trees of various diameter depending on the canopy density (according to Golikov and Starodubtseva).

Diameter at breast height, cm	**Canopy density**		
	0.8 and more	**0.6-0.7**	**up to 0.5**
	needles weight (kg)		
4	0.9	3.5	6.7
8	3.9	7.3	12.9
12	7.0	12.2	19.5
16	11.3	17.7	27.9
Diameter at breast height, cm	Canopy density		
	0.8 and more	0.6-0.7	up to 0.5
	needles weight (kg)		

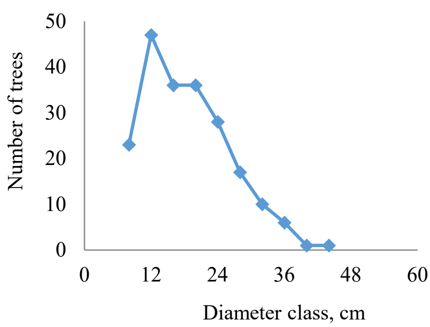
20	16.3	24.4	36.6
24	22.1	32.6	45.1
28	28.6	41.4	54.5
32	36.3	49.4	64.0
36	44.4	58.8	74.1
40	54.3	69.8	85.4
44	64.6	80.8	94.6
46	76.3	92.2	105.8
52	87.0	103.7	114.9
56	100.6	114.4	125.0
60	114.4	126.6	137.3

The obtained values were converted into dry weight (a conversion factor of 0.455). A universal value of 0.5 was used to convert dry needles weight to carbon.

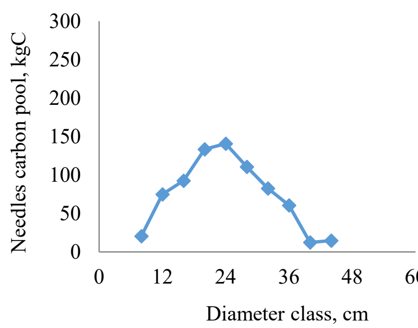
Data processing was carried out in the Excel spreadsheet software program and the Curve Expert program.

3 Results and discussion

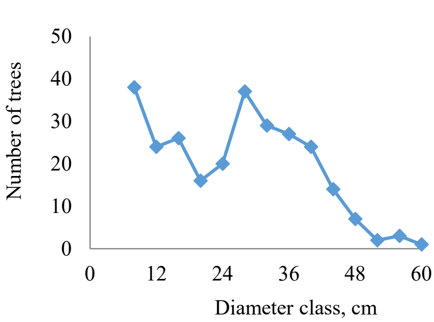
A stand density determines trees diameter and the structure of needles carbon pool. Notably, the stand diameter structure differs from the structure of needles carbon pool. Figure 2 shows the diversity of needles carbon pool structure in some of the research plots (RP No.1, 4, 9, 10).



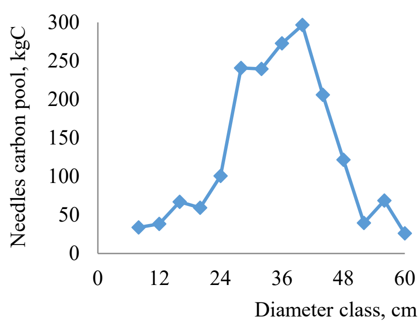
A) Trees distribution by diameter class (RP No.1)



B) Needles carbon pool distribution by diameter class (RP No.1)



C) Trees distribution by diameter class (RP No.4)



D) Needles carbon pool distribution by diameter class (RP No.4)

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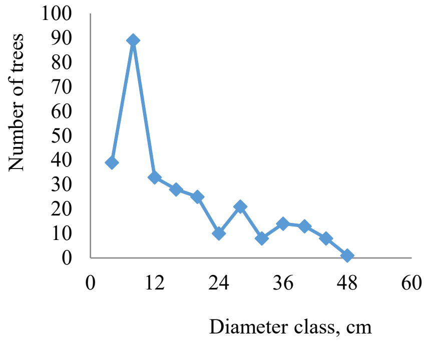
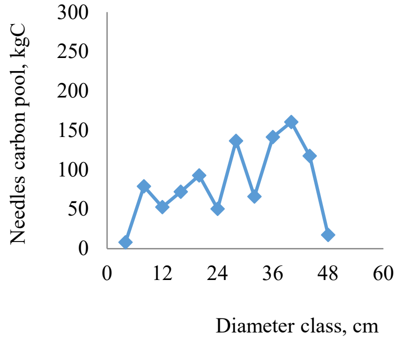
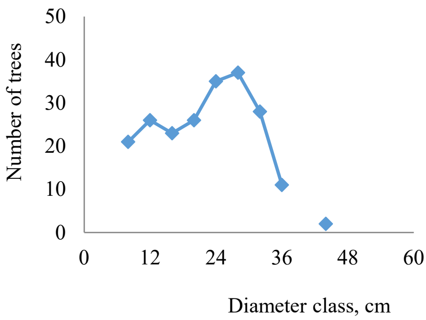


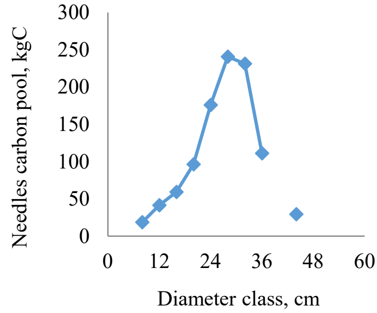
E) Trees distribution by diameter class (RP No.9)



F) Needles carbon pool distribution by diameter class (RP No.9)



G) Trees distribution by diameter class (RP No.10)



H) Needles carbon pool distribution by diameter class (RP No.10)

Fig. 2. Stands diameter structure and needles carbon pool distribution by diameter classes.

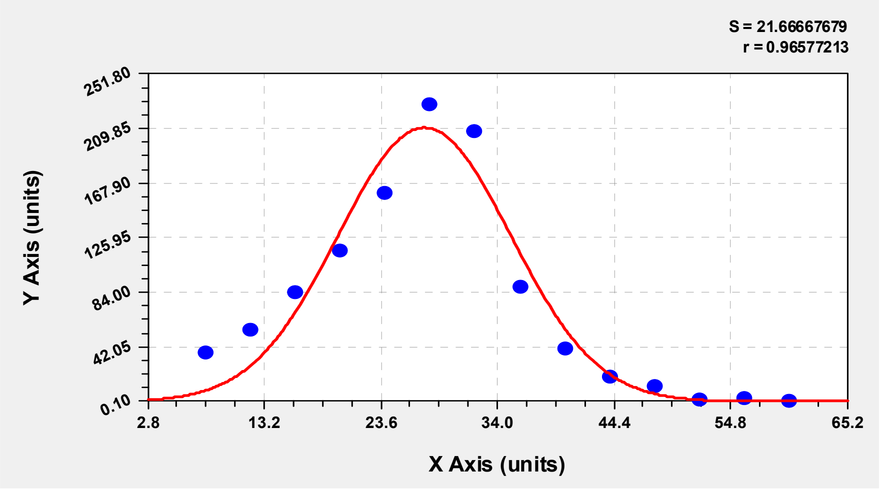
The diagrams indicate the difference in the distribution of the number of trees and the mass of needles in trees of different sizes. On RP No.1, for example, the most trees are of the 12 cm diameter class while the maximum needle carbon pool is concentrated in trees of the 24 cm diameter class. A similar pattern was observed on the rest of the research plots, except for RP No.10, where the most of trees as well as the largest needles carbon pool corresponded to the trees of 28 cm diameter class. It can be stated for the study area that there is no certain category of trees which needles act as the major carbon pool. It depends on the structure, density and size of trees in pine stands.

At the next stage, stands diameter structure and needles carbon pool distribution by diameter classes was modeled. The Gaussian function turned out to be the most adequate:

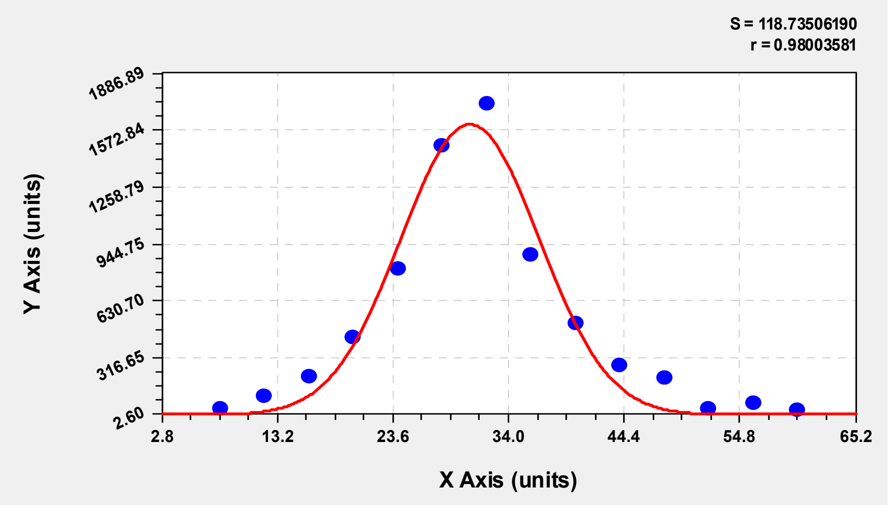
$$Y = a * e^{\frac{-(\bar{x}-x)^2}{2 * \sigma^2}}, \quad (1)$$

where Y – function value (output variable);
a – the maximum point of the output value;
$\bar{x}$ – the mean value of the input variable;
x – input variable;
Ϭ – standard deviation.

Since the Gaussian function is based on average value, the data set has been divided into the following average diameter parameters (14, 16, 20, 22, 24, 28 cm). 20 and 28 cm diameter classes were a combined material of measurements conducted on several research plots. Figure 3 shows such a combined measurement.



A) Trees distribution by diameter class
X – diameter class, cm; Y – number of trees



B) Needles carbon pool distribution by diameter class
X – diameter class, cm; Y – needles carbon pool, kgC.

Fig. 3. Approximations of the stands diameter structure and needles carbon pool distribution by diameter classes by the Gaussian function (average diameter of pine trees is 28 cm).

Table 3 shows the main characteristics of the studied pine stands by the Gaussian function. It should be noted that the main characteristics of the Gaussian function can be modeled depending on one or another factor, since the average value, standard deviation and maximum value depend on environmental factors. Thus, considering the climate change, we used the mean annual temperature in Krasnoyarsk for the following periods (1991-2000 – +13.9^0; 2001-2010 – +14.4^0; 2011-2021 – 14.6^{0}C) as a criterion for modelling the structure of needles carbon pool [13]. The periods were selected since the forest inventory was conducted in 1994 and 2021.

Table 3. The Gaussian function parameters of the stands diameter structure and needles carbon pool distribution by diameter classes.

Average diameter, cm	Maximum value, a	Mean value, $\bar{x}$	Standard deviation, б
Trees distribution by diameter classes			
14	253	13	6
16	78	13	7
20	286	17	8
22	109	22	7
24	49	22	9
28	211	27	8
Needles carbon pool (kgC) distribution by diameter classes			
16	161.2	19.5	8.75
20	1036.2	23.2	8.04
22	523.2	25.1	6.45
28	1063.4	30.5	6.22
Needles carbon pool (%) distribution by diameter classes			
16	18.6	19.5	8.75
20	19.7	23.2	8.06
22	18.6	23.2	8.89
28	23.5	30.5	6.23

Figure 4 shows a correlation between the Gaussian function parameters (%) of the distribution of needle carbon pool and mean annual temperature.

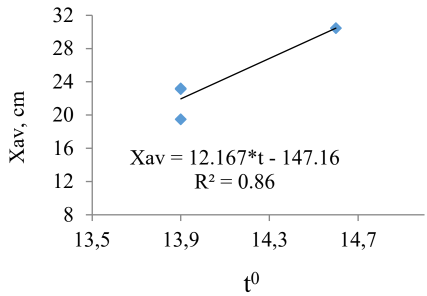
Notably, the correlation between stands structure and external and internal factors is multifactorial. The mean annual temperature is one of the factors that determine growth rate and mortality. The correlation is linear due to the insignificant change in the mean annual temperature. All regressions were characterized by rather high values of the coefficient of determination (R^2=0.86-0.95). As the mean annual temperature increases, the average tree diameter increases as well, while the value of the standard deviation (%) decreases, and the value of the maximum carbon stock (%) of the initial diameter classes increases.

The resulted Gaussian model made it possible to model the structure of needles carbon pool in pine stands on abandoned agricultural land considering temperature changes:

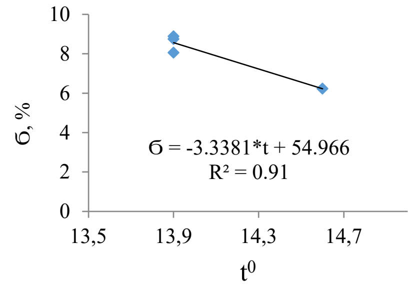
$$\text{MYX (\%)} = (6.4857*t-71.201)*e^{\frac{-((12.167*t-147.16)-x)^2}{2*(-3.3381*t+54.966)^2}}, \quad (2)$$

where MYX – needles carbon pool, %;
t – mean annual temperature, C^0;
x – diameter class, cm.

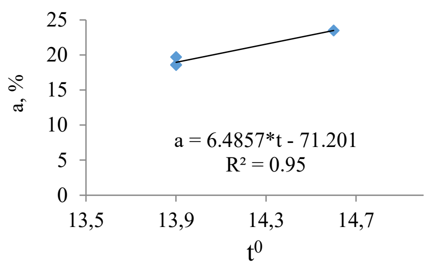
The range of the equation is as follows: temperature (t^0=13.9-14.6); diameter class (4-60 cm); needles carbon pool (0-100 %).



A) Correlation $X_{av}=f(t^0)$



B) Correlation $б=f(t^0)$



C) Correlation $a=f(t^0)$

Fig. 4. Correlations between Gaussian function parameters and the mean annual temperature.

4 Conclusion

The diameter structure of middle-aged and mature pine stands growing on abandoned farmland, revealed the following.

- Pine forests on fallow lands are even-aged. However, they differ in stand characteristics and their structure due to the density (stocking and density).
- The stand diameter structure differs from the distribution of needles carbon pool. In the study area, there is no certain category of trees that sequester the maximum amount of carbon in their needles. It depends on the stands structure and density as well as on the size of trees in pine forest.
- The Gaussian equation is an optimal function for modeling the stands diameter structure and needles carbon pool. According to this function, it is the average trees in relation to a particular forest stand that accumulate the maximum needles mass. Thus, forest management should be focused on saving medium-sized pine trees.
- Such an environmental factor as the mean annual temperature was used to model the distribution series of needles mass (%) by diameter classes. In recent years, there has been a trend towards an increase in temperature, which influence both the growth rate and the structure of forest stands. As a result, an equation was obtained that consider the change in the average diameter, standard deviation and maximum value from the temperature trend.

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